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THE INSTITUTE OF HIGH TEMPERATURES OF THE USSR ACADEMY OF SCIENCES THE MOST IMPORTANT RESULTS OF SCIENTIFIC RESEARCH IN 1969

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THE INSTITUTE OF HIGH TEMPERATURES OF THE USSR ACADEMY OF SCIENCES THE MOST IMPORTANT RESULTS OF SCIENTIFIC RESEARCH IN 1969

ABSTRACT. The research work conducted at the Institute of High Temperatures of the Academy of Sciences, USSR, in 1969 is summarized. This work encompassed the following four areas: Research on thermophysical and electrophysical properties of matter at high temperatures; research on high temperature processes of heat exchange, mass exchange, and physical gasdynamics; development and research on new heat-resistant construction materials; research on development of equipment for a direct transformation of heat into electric energy by means of magnetohydrodynamics generators, and also new types of power generating equipment.

Articles, inventions, and books of the Institute staff published in 1969 are listed in an Appendix.

The Institute of High Temperatures of the Academy of Sciences, U.S.S.R. /3 (IHTAS) was formed in 1962, based on the Laboratory of High Temperatures, Academy of Sciences, U.S.S.R., created in 1960. At the present time IHTAS is an enterprise which includes about 1000 workers. Five academicians, one associate member of the Academy of Sciences, U.S.S.R., 16 Ph.D's, and 109 staff members with advanced degrees in science work at the Institute.

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* Numbers in the margin indicate the pagination in the original foreign text.

There is a special design department with industrial experience, numbering more than 500 employees. A BSEM-4 computer was introduced in the Institute in 1969.

Along with the research work in the Institute of High Temperatures, IHTAS directs the scientific work of the numerous branches of the Special Design Department dealing with new equipment, the U-02 and U-25 devices , and the Ministry of Power and Electrification of the U.S.S.R.,who do research on the direct transformation of thermal energy into electric energy by the magnetohydrodynamic method.

The Institute of High Temperatures of the Academy of Sciences, U.S.S.R. falls within the jurisdiction of the Division of Physical-Technical Power Studies of the Academy of Sciences, U.S.S.R.

In 1969 the Institute of High Temperatures of the Academy of Sciences, U.S.S.R. (IHTAS) continued to expand scientific research in four main directions: /4

(1) Research on thermophysical and electrophysical properties of matter at high temperatures;

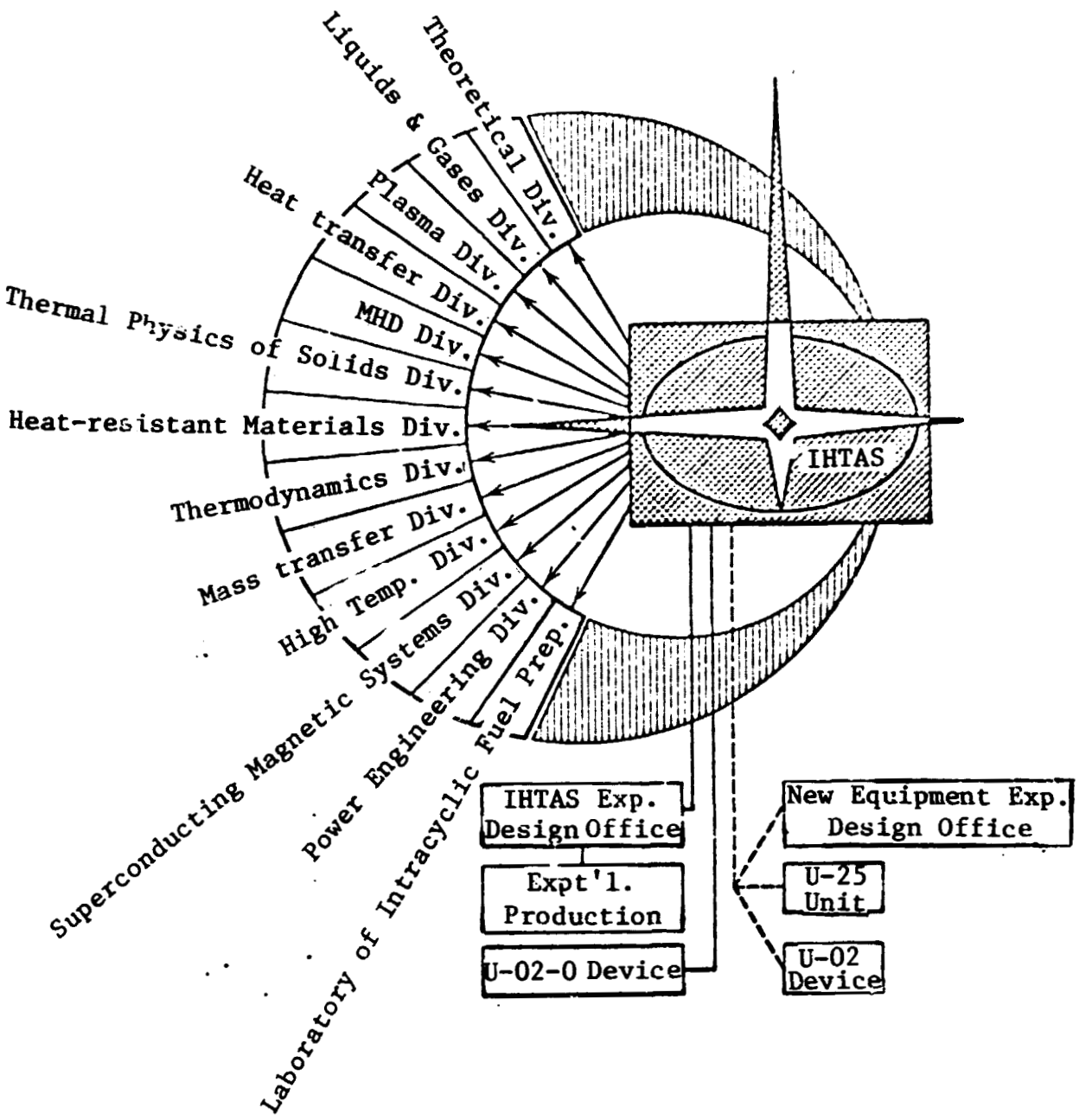
(2) Research on high temperature processes of heat exchange, mass exchange, and physical gasdynamics;

(3) Development and research on new heat-resistant construction materials;

(4) Research on development of equipment for a direct transformation of heat into electric energy by means of magnetohydrodynamics generators, and also new types of power generating equipment.

The main results of scientific research at IHTAS in 1969 are briefly summarized below.

Scientific Research Divisions



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RESEARCH ON THERMOPHYSICAL AND ELECTROPHYSICAL PROPERTIES OF MATTER AT HIGH TEMPERATURES

/5

SECTION 1

Research on a Low Temperature Plasma

For several years the Plasma Division of the Institute has performed experimental research on the transfer and optical properties of a low temperature plasma in gas discharge stabilized by a wall. In 1969 research was concluded on the electrical conductivity, thermal conductivity, total and spectral emittance (λ=2500Å - 10,000Å) of air and CO_2 at P = 1 atm and T = 6000 - 15,000°K.

A high pressure device ($P \leqslant 10$ atm) operating with argon was designed based on a stabilized arc. Studies were made of the spectral brightness distribution of continuous emission of a high pressure plasma. It was found that in the infrared and visible spectral regions the brightness temperature of such a source may be regulated between 4000 to 12,000°K. At the present time, systematic studies are being performed on the parameters of a plasma obtained with a device, whose purpose is to study its possible utilization as a brightness standard.

The 1969 experimental studies were continued on the properties of a plasma with a mixture of inert gas and alkali metal. In particular, measurements were made of the intensity of the continuous emissions of an argon-potassium plasma produced by free-transitions in the field of a neutral argon atom, and the electrical conductivity of a helium-potassium plasma.

Figure 1 compares the kinetic electrical conductivity coefficient for argon-potasium (1) and helium-potassium(2) plasma.

In order to study experimentally the properties of a dense, non-ideal plasma, research has been performed on the behavior of a helium plasma in a glow-discharge at cryogenic temperatures. Preliminary experimental data have been obtained.

Research is being continued on the viscosity of a low temperature plasma of different gases. In 1969 the longitudinal pressure gradients were measured in an arc discharge stabilized by a wall in an atmosphere of nitrogen and air. A precise method of measuring the plasma velocity in the arc channel has also been developed.

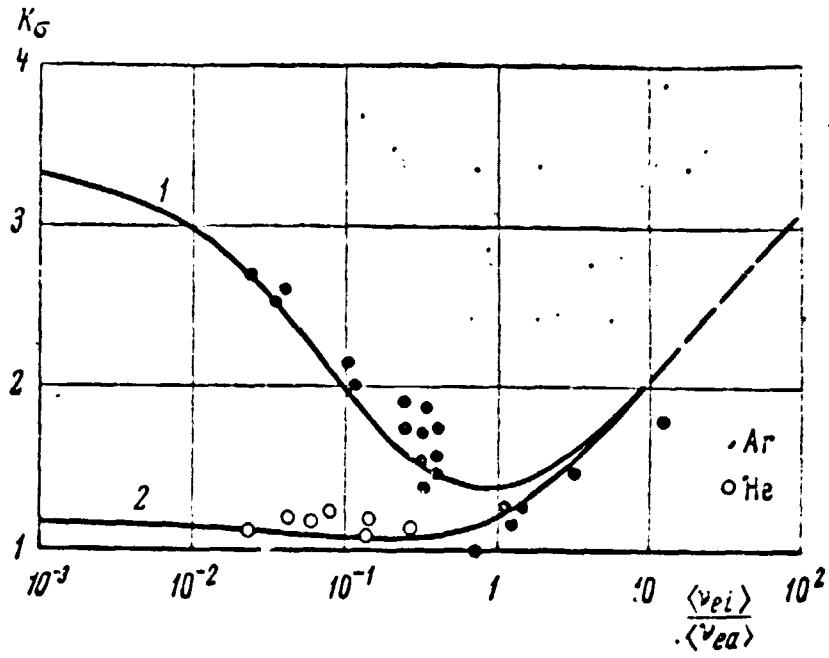

Figure 1.

The Plasma Division performs /6 experimental research on the interaction of electromagnetic fields with a plasma in the microwave range.

In particular, the velocity of the ionization front propagation has been measured in a strong superhigh frequency field in argon, nitrogen, and air at pressures ranging from 10 to 760 mm Hg. The measured velocity values in the nitrogen and air are characteristic for a process which is similar to the flame propagation in slow burning. At atmospheric pressure in argon, the measured velocity values of the front reach 1000 m/sec for a flux density of superhigh frequency energy on the order of 3 V/cm^2 (Figure 2).

The Theoretical Division has analyzed the possibility of dividing a dense (greatly non-ideal) plasma into two phases; "a plasma gas" and "plasma liquid"

which differ in terms of the concentration of charged particles. The less dense phase ("gas") is in a state close to that of an ideal gas. In the denser phase ("liquid") the free charges strongly interact with each other, and the energy of this interaction exceeds the thermal energy. A theoretical discription of such a plasma liquid is only possible within the framework of a quantum approach. The dashed line in Figure 3 show the possible variations of curves for phase equilibrium.

The possible existence of a metastable supercooled dense plasma is investigated. The hypothesis is advanced that ball lightning represents a metastable supercooled air plasma at normal temperature.

Two methods are used when compiling a dense plasma theory: the method of machine experiment and the method of the quantum field theory. In the first method, psuedopotentials which take into account the quantum effects in the /7
vapor approximation are used for calculating a nondegenerate plasma. In this case, the psuedopotential coincides with the Coulomb potential at great distances, but it is finite for small differences. The psuedopotentials for cesium are examined. The Monte Carlo method is used for test calculations of thermodynamic properties of hydrogen and cesium plasma.

The second method uses the Green function procedure, which gives a description of the thermodynamic and transport properties of systems with strong interaction. This method was used to obtain a varial type of expansion for the electroconductivity of a slightly non-ideal, partially ionized plasma. The use of diagram technique made it possible to calculate the quantum effects produced during the simultaneous scattering of an electron by several atoms.

In a slightly ionized plasma the non-ideal properties may be caused also by electron-atom interactions. It is shown that under some conditions a greatly non-ideal plasma acquires properties which are characteristic for certain semiconducters. Its electroconductivity sharply increases. The possibility of a phase transition of the first type arises.

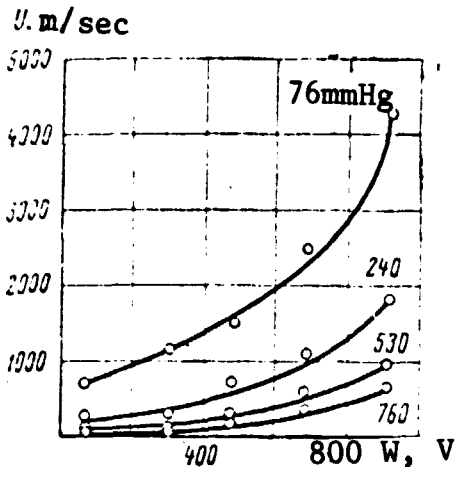

Figure 2.

In 1969, research was continued on elementary processes.

The transition cross sections of excited atoms were calculated as a result of the collision with electrons from n-state (n-main quantum number) into the $n + \Delta n$ state for n = 3 - 10 and $\Delta n = 1 - 10$. The results are given in the form of simple asymptotic formulas for cross sections and constants of excitation rates of atoms by electron collision.

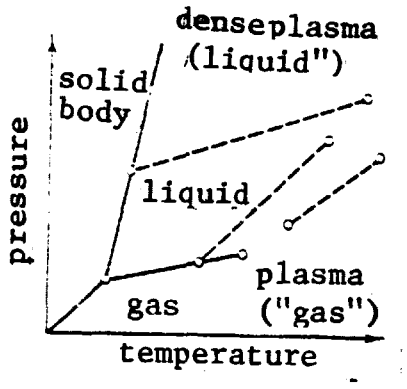

Figure 3.

Methods were developed for calculating the volume interaction potentials at large distances between nuclei. These potentials are used in calculating the cross section of resonance collision processes of atomic particles, and also the elastic scattering cross section of atoms, excited atoms, and molecules.

The elastic scattering cross sections obtained are used for finding the kinetic transport coefficients in a gas.

An approximate method is developed for calculating the cross section of photoionization and forces of spectral line oscillators of atoms and positive ions. This method is based on the analytical wave functions of a self-consistent field for lower state and Coulomb functions for the upper state. Analytical expressions are obtained for a matrix element of the radius vector for bound-bond and bound-free transitions. The photoionization cross sections and the oscillator force densities are calculated for transitions from the lower states of atoms and ions of nitrogen and oxygen for different multiplicities.

These data are necessary for obtaining the optical properties of high temperature air, which continues to be studied in the Theoretical Division. The staff members of the Division have developed a method for calculating the absorption coefficients and intergral characteristics of air at temperatures up to 100,000°K. /8

Just as previously, an important phase of work in the Division is to study a nonequilibrium low temperature plasma.

The study of nonequilibrium is applied to the channel of a closed cycle magnetohydrodynamic generator. It is very important to determine the length at which the requisite level of plasma conductivity is established. This problem is solved with allowance for the transport of emission and instabilities characteristic for a plasma in a channel of a magnetonydrodynamic generator. In 1969, a criterion was obtained for development of ionized instability in the relaxation zone.

Studies of Liquids and Gases

In the Division of Liquids and Gases, many studies were made of the thermophysical properties of matter in liquid and gaseous phases at high temperatures.

Just as in previous years, the direction of research and specific objects of study were selected so that the questions of technology could be satisfied on reliable computers based on the thermophysical properties of different substances, and also so that scientific problems could be solved.

In 1969, research was continued on the thermophysical properties of liquid metals and their vapors, including alkali metals, mercury, etc., the melted oxides of metal such as B_2O_3, Al_2O_3, and others, lithium hydride in liquid and vaporous states, dissociated gases such as N_2O_4, and also hydrogen, different hydrocarbons, inert gases, etc.

The 1969 experimental research was concluded on the density, enthalpy, viscosity, and surface tension of boron oxide up to a temperature of 2000°C. The results obtained, in particular the temperature dependence of the viscosity of B_2O_3, displayed specific features. At temperatures of 1500-1600°C, the dependence of viscosity on temperature changes, which provides a basis for a assuming the presence of structural reconstruction in the melt.

The density of B_2O_3 was studied by the method of hydrostatic weighing. Special measures were employed to establish an almost isothermal zone in a device having a height of the order of 150 mm and diameter on the order of 100 mm. The maximum temperature difference in this zone did not exceed 3 - 4°C in height for a temperature level of 1900°C.

Boron oxide enthalpy was studied by means of a boiling calorimeter, whose construction was similar to that used previously when studing the enthalpy of alkali metals. The ampule with the sample was heated in a special high temperature furnace, and when the specified temperature was reached the ampule was dropped into the calorimeter.

The viscosity of the melted boron oxide was measured by a stationary rotational method based on the angle of torsion of the elastic filament on which the solid body was placed, and lowered into a vessel with the melt being studied. Great attention was given the dehydration of B_2O_3 in the studies, since the presence of water greatly changes the melt viscosity. /9

The surface tension was measured by opening the cylinder with a narrow edge. The boron oxide displayed anomalous surface tension in the temperature interval studied. The surface tension coefficient of B_2O_3 increased with the temperature increase. In particular, between 700 to 2000°C the surface coefficient increased from 73 to 112 dyne/cm. As the upper limit of this temperature interval was approached, there was a slower increase in the surface tension of the melted boron oxide.

In 1969 research was continued on the thermophysical and electrophysical

properties of alkali metals both in the pure form and in the form of melts.

In particular, the density of potassium was measured up to a temperature of 1500°C at pressures up to 60 kgf/cm^2. Since the scatter of the experimental points was very small, and the experiment accuracy was quite high (maximum error was ~0.25%), it was possible to determine quantitatively the compressiblity of liquid potassium in the given pressure range.

Interesting experimental data were obtained in studies of the electroresistance of solutions of sodium with small additions of lithium or potassium. Measurements were performed at temperatures up to about 1100°C.

The study of the Na - K alloy viscosity performed in the 20 - 1000°C temperature range confirmed the previously advanced assumption regarding the existence of a chemical compound NaK_2 at the eutectic point. It is interesting that this effect begins to appear at temperatures exceeding the alloy melting point by 200 - 300°C, which coincide with the previously observed temperatures of structural transitions in pure potassium and sodium.

The boiling point method was used to study the temperature dependence of the saturated mercury vapor pressure in the 550 - 900°K and 0.2 - 26 kgf/cm^2 parameter interval.

A theoretical study was made of the pressure of dissociation products and the composition of the vapor phase of lithium hydride on the saturation line in the 1000 - 2000°K range.

During the vapor formation of lithium hydride, the condensed medium was greatly enriched with lithium due to the dissociation reaction of LiH vapor. This effect must be taken into account when designing a specific apparatus which uses lithium hydride. The analytical dependences were obtained and calculations were made of the change in the condensed medium composition of the Li - LiH system during evaporation in a closed vessel as a function of temperature, initial concentration, and initial filling of the volume. /10

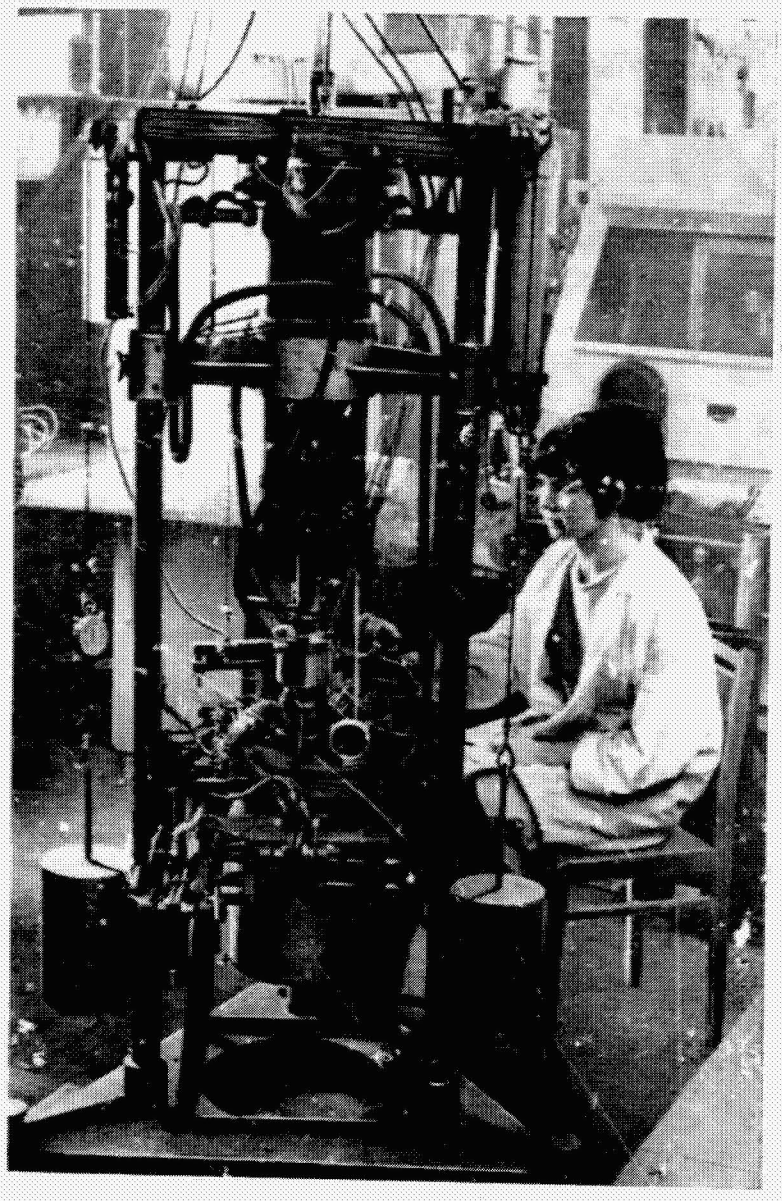

Figure 4.

An experimental study of the thermophysical properties of lithium hydride was made along with the theoretical studies. In particular, in the experimental arrangement shown in Figure 4, enthalpy was measured up to a temperature of 900°C, as well as the melting point of lithium hydride. A mixing method using a boiling calorimeter was employed in these measurements.

In 1969, experimental studies were continued of the viscosity of the dissociating system

$$N_2O_4 \rightleftarrows 2NO_2$$

in the temperature interval 250 - 420°K and the pressure interval 25 - 750mm Hg, which corresponds to a degree of association from 0.079 to 0.999.

The relationships were obtained for calculating the viscosity in the given interval of state parameters. It was found that the dissociating system may beregarded as a mixture of two gases having a variable composition, wnose viscosity deviates very little from the simple additive law. On the basis of extrapolated relationships of the viscosity of pure N_2O_4 and NO_2, the potential interaction parameters of these substances were calculated. This work corroborated the conclusions of the theory stipulating the chemical reaction has practically no influence on the viscosity of the dissociating mixture. /11

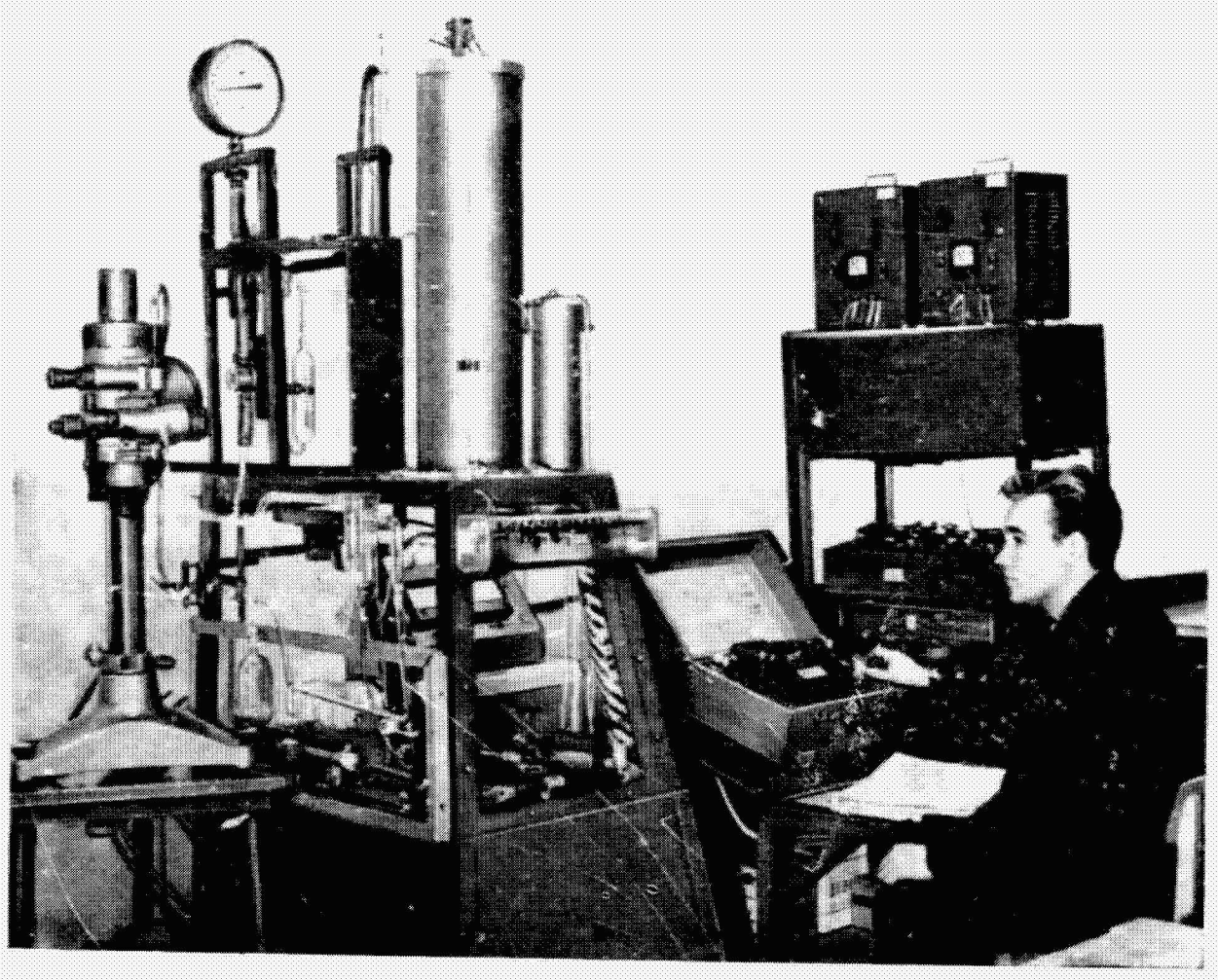

Figure 5.

In 1969 studies, which had been carried out for several years, were concluded on the thermophysical properties of hydrogen -- viscosity, thermal conductivity, P - v - T - dependence, etc. In addition all the existing data in the temperature interval 14 - 2000°K and the pressure interval 1 - 1000 bar were analyzed and generalized.

The experimental studies were made of the viscosity of vapors of several organosilicon compounds and high molecular hydrocarbons at 150 - 450°C at pressures of 0.1 - 0.5 atm. /12

For the studies, a new variation of the capillary viscosimeter with a hermetic closed circulating circuit was used (Figure 5).

In order to bring the existing handbooks up to date, a precision measurement of P-v-T of nitrogen dependence in the near-critical region of state parameters was made, as well as the thermal conductivity of neon in the 400 - 2400°K temperature interval.

In 1969, theoretical studies were continued on transport phenomena in gases with internal degrees of freedom. Particular attention was given to a study of the limits of applicability of classical mechanics methods in calculations of the thermodynamic and kinetic properties of molecular gases.

Numerical methods of machine experiment (Monte Carlo and molecular dynamic methods) were developed and used at the Theoretical Division for studying the properties of liquids and real gases.

The Monte Carlo method was used for a large canonical ensemble, making it possible to predict theoretically the phase transistions and to calculate the thermodynamic values at the points of phase transistions and homogeneous phases. The phase transition is obtained as a direct result of the initial expressions of Gibbs' statistics and the specific form of the molecular interaction forces. The vapor-liquid phase transition in inert gases is studied as an example.

A variation of the Monte Carlo method was proposed for studying the thermodynamic properties of quantum liquids, making it possible to perform calculations within the framework of the Feinman formulation of quantum statistics.

A method based on the formulas of Coubeau (theory of linear response) and representing the development of molecular dynamic methods has been proposed for studying the transport properties of liquids and real gases.

Studies of Solids

In 1969, the Division of Thermophysics of Solids completed a complex study of the influence of anisotropy on the following thermophysical properties of pyrolitic graphite:

(1) The integral semispherical emissivity from a surface parallel to the crystallographic axis "a" (in the 1000-2200°C temperature interval) and from a surface parallel to the crystallographic axis "c" (in the 800 - 1600°C temperature interval);

(2) Electrical resistance in the direction of the "a" axis (20 - 1900°C) and in the direction of the "c" axis (20 - 1500°C);

(3) Thermoconductivity in the direction of "c" axis (900 - 2200°C). /13

As a result of the studies, strong anisotropy of the electrical properties of pyrographite was determined: specific electrical resistance in the direction of the "c" axis exceeded by three orders of magnitude the specific electrical resistance in the direction of the "a" axis; the integral semispherical emissivity of the surface parallel to the "c" axis was 30% greater than the emissivity of the surface parallel to the "a" axis.

It was established that the thermoconductivity and electrical resistance of pyrographite depends essentially on the treatment temperature. For example, for samples of pyrographite subjected to thermal processing at 3100°C, the thermoconductivity increased by a factor of three, while the electrical conductivity increased by one order of magnitude, as compared with samples subjected to thermal processing at 2600°C.

In 1969, development was completed of two new experimental devices for measuring the integral semispherical emissivity of a wide class of conductive materials as well as the normal integral emissivity of semitransparent materials.

One distinctive feature of the first device is the use of electron heating, which solves the problem of reaching a high measurement temperature (±3-5%) for small sample dimensions (diameter 5 - 8 mm, length 10 - 20 mm).
The upper temperature limit was established by the temperatures for the beginning of intense sample sublimation. This device was used to first study the integral semispherical emissivity of tungsten moncrystals up to 2900°C, crystals of molybdenum up to 1900°C, and rhenium up to 2700°C. Data were also obtained for five nickel-rhenium alloys up to temperatures of 1100 - 1200°C, and certain ternary alloys of the molybdenum-tungsten-rhenium system.

The second device for studying the integral normal emissivity of semitransparent media was based on an original method, which makes it possible to eliminate completely the incidence of scattered and reflected furnace emission on the thermal receiver, and to increase in this way the measurement accuracy. This was done by using a tubular heater, which was dropped into a special collector at the desired time, and the emission of the remaining sample was measured by a fast device. Induction heating was used to obtain high temperatures.
At the present time, the operation of the device is checked with quartz. The experiment may be carried out in the 300–2200°C temperature range on samples of different thickness and having the shape of plates.

In accordance with the research program, in 1969, studies were continued on the thermal conductivity coefficient of structural materials as a function of temperature and the initial technological parameters. /14

In particular, data were obtained on the dependence of thermal conductivity on porosity and temperature of porous nickel, porous graphite, and several ceramics. These results make it possible to check the validity of the basic conclusions set forth by the theory of effective thermal conductivity of two-phase systems. In addition, the termal conductivities of silicon-carbide up to 1400°C and cerium-dioxide up to 1200°C were measured.

In order to increase the accuracy and reliability of the experimental data, the equipment and methods of research were further improved. At the

present high level of measurement technology, the reliability of the experimental data is limited in the majority of cases not by the accuracy of the equipment used, but by the refinement of the system of corrections which must take into consideration the deviation of real experimental conditions from an idealized experimental arrangement. In particular, it was established that the lack of isothermality of the sample inside the furnace significantly influences the reliability of data in high-temperature studies of enthalpy by the mixing method. At temperatures on the order of 1700°C the correction for lack of isothermality is commensurate with the error of an optical pyrometer of the EOP-51 type. As a result of these studies, reliable values were obtained for the correction for lack of isothermality in the sample. The use of these corrections provides increased reliability of temperature measurements and experimental data on the whole.

A detailed experimental study of enthalpy and heat capacity of zirconium, niobium, and tantalum carbides in a wide temperature range of 900 - 3000°C was concluded. Data were obtained at the same time on the enthalpy and heat capacity of the alloys of zirconium carbide-niobium carbide of differing compositions. The research results are extremely accurate and may be used when compiling reference data on thermal constants.

The Division has participated in the international program of the Commission Working Group on high temperatures and high-melting substances of the International Union of Theoretical and Applied Chemistry.

This program encompasses the study of the melting point of high-melting substances which could be recommended as secondary melting points for the International Practical Temperature Scale (IPTS). The first stage studies the melting point of corundum for unified samples; the preliminary results were transmitted by the Institute to the participants in the Working Group. The Division obtained melting points of corundum (2051.4 ± 4.5°C) and the solidification points of corundum (2050.8 ± 3.7°C) which closely coincide with the value of 2050 ± 4°C (IPTS,1948) recommended on the basis of averaging measurements in nine different laboratories throughout the world. The equipment used /15

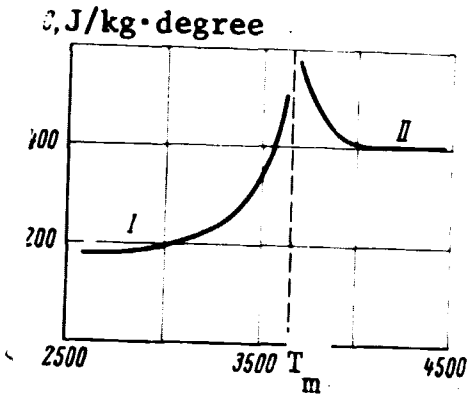

Figure 6

for the temperature measurements was calibrated with a high degree of accuracy according to the All-Union Scientific Research Institute of Meteorology imeni D. R. Mendeleyev.

Theoretical studies are presently being performed also.

In 1969, the total results of the individual phases of research were compiled. Methods were developed for taking into account the effects of anharmonicity which influenced the temperature dependence of the thermophysical values of solid metals at high temperatures. A new dynamic model was proposed for the liquid state of metals which explained several characteristics of metallic liquids (the reasons for the lack of long-range order, the dependence of Cp on temperature, the inactive nature of self-diffusion, etc.). Methods were found for compiling the equations of state of solid and liquid metals at high temperatures. These equations were used to calculate the thermophysical properties of certain metals in solid and liquid phases, including heat capacity and thermal expansion of liquid tungsten.

In order to study the state of metals at high temperatures, in 1969, the rupture of conductors under the influence of an electric current was studied. Primary attention here was directed toward the melting, and also the later stage of rupture — the disappearance of the electroconductivity of the liquid metal.

A method was developed for measuring the temperature close to the melting point. This method (together with the oscillograph determination of incoming energy) was used to measure the heat capacity of tungsten in the 2300 - 3300 and 3400 - 4100°C temperature intervals.

Figure 6 shows data on the specific heat capacity of solid (I) and liquid (II) tungsten in the 2500 - 4500°K temperature range. Data were first obtained in the liquid phase region.

Data were obtained for the later rupture stages, which indicates that its conversion into sol with particle dimensions on the order of several hundreds of interatomic distances contributes to the disappearance of the liquid metal electroconductivity. Sol was observed by means of an electron microscope after the disruptive current was abruptly turned off, which was done before the beginning of electrical breakdown in the rupture products. The smaller the electroconductivity at the moment the current was turned off, the smaller were the particles obtained. The state of the ruptured metal after the disappearance of metallic electroconductivity was very important for the subsequent process — the development of a discharge and formation of plasma.

In 1969, the Division of High Temperature Processes performed studies on the kinetics of the interaction of carbides with working gases of varying composition, and they established the permissible oxygen admixtures in the working gas. Recommendations were made on the possible use of technical hydrogen during stand tests. /16

Studies in High-Temperature Chemical Thermodynamics

For several years the Division of Chemical Thermodynamics of the Institute has carried out systematic studies to establish the composition of different chemical systems in the gaseous state and to determine the molecular constants (structures of molecules and other molecular constants, dissociation energy, heat of formation, and heat of sublimation) necessary to compile tables of gas thermodynamic properties. There were also necessary to formulate fundamental reference information on the thermodynamic properties of substances.

In 1969, the main items studied were compounds of alkali and alkali-earth metals, as well as metals of transition groups.

A high-temperature MS 1301 mass spectrometer was used to study the composition of vapors of the molybdate of cesium, uranium, and the magnesium oxide-boron oxide system. It was established that cesium molybdate volatilizes almost without decomposition. A strong temperature dependence was found

for the mass spectrum of Cs_2MoO_4, which was similar to the temperature dependence of the mass spectra of compound organic substances (as the temperature increases, the relative intensity of ions Cs_2MoO_4+ in the mass spectrum sharply decreases). The sublimation heat of Cs_2MoO_4 at 1150°K was calculated from the relationship of the total intensity of all ions formed during ionization of Cs_2MoO_4 and was found to be 73.5 ± 1 kcal/mole.

In vapors over MgO - B_2O_3, molecules of $MgBO_2$ and MgB_2O_4 were detected along with magnesium, oxygen, and boron oxide. The thermal effects were determined along with the entropy change for the reaction

$$MgO(тв) + B_2O_3(г) = MgB_2O_4(г),$$
$$\Delta H_{1925} = 27{,}4 \pm 1{,}1 \text{ kcal/mole}$$
$$\Delta S^\circ_{1925} = 8{,}9 \pm 0{,}6 \text{ kcal/mole·degree}$$
$$MgO(тв) + Mg(г) + B_2O_3(г) = 2MgBO_2(г),$$
$$\Delta H^\circ_{1909} = 66{,}2 \pm 2{,}8 \text{ kcal/mole}$$
$$\Delta S^\circ_{1909} = 26{,}2 \pm 1{,}5 \text{ kcal/mole·degree}$$

A study of uranium vapor composition revealed that at $T \leq 2420$°K the partial pressure U_2 does not exceed 10^{-5} of the partial pressure of atomic uranium. The existence of U_2O_2 molecules was established simultaneously in the uranium-oxygen system; the equilibrium constant of the reaction $U_2O_2 \rightleftarrows 2UO$ equalled $1 \cdot 10^{-1}$ atm at 2350°K.

Concurrently with the Mass Spectrometer Group of the Chemistry Department of Moscow State University, a study was made of the ion appearance potentials /17 in the mass spectra of the vapors of alkali metal metaborates. The rupture energies of the M-BO_2 (M-K, Rb, Cs) bond, determined from the appearance potentials of M+ ions, closely coincide with the vapor pressures of MBO_2 calculated from measurements in 1967-68. The appearance potential of the BO_2 ions was used to determine the affinity of the BO_2 radical to an electron, which equalled 0.7 ± 0.1 eV.

In 1969, a study of the structure of molecules B_2O_3, $NaBO_2$, KBO_2, $RbBO_2$, the suboxides Ba, In, and Tl, and also Re_2O_7 and Re_3Br_9 by the electron

diffraction method was completed.

In the last fifteen years, several studies have attempted to determine the structure of B_2O_3 and MBO_2 molecules. However, in actuality it is only possible to establish the existence in these molecules of the linear group OBO. The determination of the BOB angle in B_2O_3 and the position of the M atom in MBO_2 was difficult due to the "washing out" effect of the molecular features of the diffraction phenomenon, caused by the low frequencies of deformation vibrations. This phenomenon decreases the contribution made by molecular characteristics (responsible for individual vapors of the nucleus) to the total scattering with an increase of the scattering angle. Therefore, in 1969, primary attention was directed toward a study of the diffraction phenomenon in the region of low scattering angles. As a result of a study using a device with a distance from the scattering region to the photographic plate of ∿1000 mm, $\angle$ BOB in B_2O_3 (132 ± 5°), and the distances of Na-O, K-O and Rb-O in the corresponding metaborates (2.14; 2.36 and 2.54 Å) were established. Somewhat less reliable data were obtained on the valence angles M-O-B which equal 109 ± 5 and 102 ± 5° in $NaBO_2$ and KBO_2, respectively. It must be noted that, according to the data obtained, in MBO_2 molecules there is a sharp increase in the length of the M-O bond as compared with the molecules of the oxides and hydroxides of these metals.

The molecules Ga_2O, In_2O and Tl_2O were studied to clarify the electronographic determination of the configuration of such molecules as M_2O with low frequencies of deformation vibrations. It was found that, due to the great populations of the excited levels of the deformation vibration, the electronographic data cannot be used to determine whether the equilibrium configuration of M_2O molecules is linear or slightly curved, without additional information. In the case under consideration, when data on the frequencies of deformation vibrations were used, it was found that GaOGa = 150 ± 10°. $\angle$ InOIn = 160 ± 10°, $\angle$ TlOTl = 145 ± 10°. The interatomic distances of M-O in these molecules equalled 1.82 ± 0.02; 2.00 ± 0.02 and 2.15 ± 0.02 Å, respectively.

In order to use the electronographic data to determine the structures of molecules containing atoms with a large nucleus charge difference, when the first Born approximation was insufficient, methods were developed to calculate the complex amplitudes by the Holtsmark and Faksen method, using the differing degree of accuracy approximation. The method developed was used for interpreting the Re_3Br_9 and Re_2O_7 electronograph. /18

In 1969, studies were continued on the electron spectra of diatomic compounds of transition metals.

When Zr powder was introduced into a shock wave propagated in nitrogen containing 1% O_2 (T= 4500-7000°K), absorption spectra of ZrO were obtained in the λλ 3390-7600Å region (system of bands $A^3\Phi - X^3\Delta$, $B^3\Pi - X^3\Delta$, $C^3\Delta - X^3\Delta$, $D\ ^3\Delta - X^3\Delta$, $b'\Delta - b'\Delta$). At the same time, previously unknown groups of bands were observed in the λλ 2646 - 3163 Å region, and a fine structure was clearly apparent in several bands. These bands will be analyzed after these spectra are observed on a high-dispersion device. In spectra of shock waves propagated in pure nitrogen, all of these bands disappear, and unknown diffraction bands appear in the λλ 2558, 2987 - 3142, 3156 - 3179 ÅÅ region. It is possible that these bands, or a part of them, belong to a zirconium nitride molecule.

The possibility was studied of obtaining absorption spectra of transition metal compounds formed after photolysis of their carbonyl compounds, and also as a result of reactions between the free metal atoms formed with other molecules. The kinetics for the formation and disappearance of Cr atoms after photolysis of $Cr(CO)_6$ (τ = 10 - 800 μsec) was studied, and absorption spectra for CrO λλ 5300 - 6400 Å, τ = 50 - 400 μsec and CrH λ 3670 Å were obtained. Unknown complex groups of bands in the λλ3440 and 4600 Å (τ < 50 μsec) region, apparently belonging to multiatomic carbonyl radicals of chromium, were also studied. A similar group of six bands in the 5180 -5230 Å (τ < 30 sec) region was obtained during the photolysis of $Mo(CO)_6$. During studies of the emission spectrum of high-current discharge in vapors of secondary magnesium in a Schuler type tube in the λλ 1800 - 1900 Å region, a new system of single-quantum bands with a violet hue consisting of four sequences was found. The band

quanta are described by the equation (in cm^{-1}): $\nu = 54244.4 + 867.2(v' + 1/2) - 8.07 (v' + 1/2)^2 - 804.6 (v'' + 1/2) + 4.75 (v'' + 1/2)^2$. After a study of the appearance conditions of this system and the difference of the vibration constants in both states from the known constants MgF, this system was attributed to the $^1\Sigma - {}^1\Sigma$ transition of the MgF+ ion. The dissociation energy of MgF+, estimated by linear extrapolation from the lower state constant, equals 4.3 eV. The ionization potential of MgF calculated from the relationship $I(MgF) = I(Mg) + + D_0(MgF) - D_0(MgF+)$ equals 7.8 eV.

A study was concluded of the energy of the M-OH bond in the GaOH and InOH molecules on the basis of the spectral photometric measurements of the $M + H_2O \rightleftarrows MOH + H$ reaction equilibrium in hydrogen-air flames, and $CO + O_2$ flames (T = 1600 - 2160°K). When the measurement results were processed, /19 assuming a linear structure of the MOH and $\nu_2 \sim 300$ cm^{-1} molecule, $D_0(Ga - OH) = = 100 \pm 5$ and $D_0(In - OH) = 93 \pm 5$ kcal/mole was found. The divergence between data obtained in studies with Ga in $CO + O_2$ and $H_2 + N_2 + O_2$ flames may be explained by the possible formation of $HGaO_2$ molecules or GaO_2 molecules in CO flames.

In 1969, the construction of several pieces of equipment for performing thermochemical measurements by the fluorine calorimetry method was completed.

A calorimeter was installed and calibrated for measuring the heat of combustion of substances not inflammable in fluorine, and an original double-chamber calorimetric pump was developed for studying substances flammable in fluorine. A comprehensive study was initiated of the thermodynamic properties of gaseous, combined hydrogen fluoride: the heats of association and P - v - T properties of HF. These studies represent a close link with the data derived from calorimetric, spectroscopic, and mass-spectrometer measurements. In the former case, the results of these measurement pertain to a real associated gas, while in the latter two cases, they pertain to an ideal gas.

In 1969, research was continued on refining the methods for calculating the thermodynamic functions of diatomic gases at high temperatures, in order

to develop a method which could be suitably used on a computer. These methods were employed for improving the calculations cited previously of the thermodynamic functions of gaseous compounds of alkali metals.

The thermodynamic properties were calculated for compounds of beryllium with oxygen, hydrogen, and nitrogen in the 100 - 6000°K range, which made it possible to refine the data given in the literature.

Based on key thermochemical data, the first summary of key thermochemical values was prepared and distributed to the Working Group of KODATA[1], as well as to the thermochemical laboratories of NBS in the United States and NFL in England. This summary was used as a basis for international recommendations.

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[1] (CODATA) - The Committee on Data for Science and Technology, International Council of Scientific Unions.

N70-37068

STUDY OF HIGH-TEMPERATURE PROCESSES OF HEAT TRANSFER, MASS TRANSFER, PHYSICAL GAS DYNAMICS, AND MAGNETOHYDRODYNAMICS

SECTION 2

Investigation of Heat Transfer Processes

The Department of Heat Transfer of the Institute conducted in 1969 compre- /20
hensive investigations of convective heat transfer processes involving a heat carrier with physical properties strongly dependent on temperature. Near-critical regions of the state parameters were included in the investigation. The year of 1969 saw the completion of two interesting studies of heat transfer in the near-critical region.

In those studies we first obtained experimental data on the distribution of heat emission around the perimeter of a rectangular pipe with one-sided heating and heat emission in turbulent flow in a circular pipe with the heat carrier being cooled. In both cases, the role of the heat carrier was played by carbon dioxide with supercritical parameters. It was shown that heat emission with cooling has a number of specific properties that do not permit us to use in the calculations the available relationships that hold true for heat transfer with the properties of the heat carrier held constant. This can be readily seen in Figure 7 which contrasts the experimental data (dots) with the calculated results based on formulas for constant properties (solid lines).

Unusual results were obtained when investigating heat transfer to gaseous NH_3 in a laminar flow in the hydrodynamic initial section of a circular pipe.

It was assumed that as the ratio of temperature of the wall and liquid increases the heat transfer decreases. The body of data obtained in this study points to an opposite conclusion. This is related, it seems, to the stronger temperature dependence of the thermal conductivity coefficient in ammonia as compared to diatomic gases.

In 1969, we completed a theoretical study of heat transfer in pipes involving laminar flow of air with variable physical properties and boundary conditions varying along the length of the pipe. The study considered both cooling and heating in the temperature range varying by a factor of 0.1 - 10 and variable boundary conditions of the first and second kind. It was shown that /21 the variability in the boundary conditions and physical properties has a considerable effect on heat transfer and hydrodynamics. Thus, for example, due to the temperature dependence of various properties, heat emission may vary by a factor of two and the coefficient of hydrodynamic resistance -- even by a factor of eight.

In 1969, new results were obtained when investigating heat emission to a dissociative heat carrier (N_2O_4). Data were collected on convective heat transfer in pipes and heat emission involved in boiling and condensation.

As we know, when nitrogen tetroxide is heated, a dissociation reaction is observed that occurs in two stages in the corresponding two temperature ranges. It was discovered that in turbulent flow in the second stage the heat emission coefficient differs considerably from the corresponding values found in the same reaction under equilibrium conditions.

The length of time spent by the gas in the heated section of the pipe was found to have a considerable effect on heat emission, this being connected with the final velocity of the second stage of the reaction.

Measurements of critical heat loads for boiling N_2O_4 in large volumes with pressures from 1 to 50 abs. atm. also testify to the strong influence

of the dissociation reaction on heat emission. The values of the critical heat loads obtained experimentally turned out to be almost two times smaller than those calculated from the available formulas. Studies of heat emission in the condensation of N_2O_4 vapors, during only the first stage of the reaction, provide us with a justification for using the usual formulas in calculations as long as the effective thermophysical properties, taking into account the recombination processes, are used.

The Department of Heat Transfer conducted a series of projects dealing with the optical properties of gases at high temperatures and heat transfer between plasma and surfaces of bodies. In 1969, we completed a theoretical investigation of heat transfer and drag involved in a turbulent flow past a plate using a dissociated and ionized air stream.

On the basis of the present-day semi-empirical theory of turbulent flow, substantiated computational relationships were obtained for heat emission and drag in the pressure range 1 - 10 abs. atm., the Re number range $Re_x 10^6 - 10^9$, and the temperature interval of the oncoming stream from 2000 to 30,000°K. In 1969, we completed experimental research into the spectral characteristics of air in the visible and ultraviolet spectrum involving the temperature range of 9000 - 17,000°K and pressure interval of 10-150 atm. Measurements were also made of the optical properties of the atmosphere of Venus at temperatures 9000 - 12,000°K and pressures of 20 - 100 atm. The experiments were done on a high-power shock tube (channel of diameter 0.1 m, length 12 m) constructed by the Institute in cooperation with the Moscow State University. (Figure 8).

Interesting results were obtained in 1969, when investigating heat transfer involved in the boiling process of surfaces with low heat conductivity coatings, and the boiling of liquid metals (sodium) in pipes. /22

It has been found that the well-known relationship between the heat flux and the thermal heat* for a boiling liquid is significantly modified with the

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* Translator's note: i.e., mean temperature difference.

introduction of a thin and low heat conductivity coating. Theoretical and experimental research has shown that an introduction of a coating may increase heat removal from a finned surface by a factor of 1.5 - 2. This is readily seen in Figure 9, where the calculated relationship (II) and the experimental points refer to the coated surface (glue VS - 10 T) with coating thickness δ = 0.005 mm, and the lower one (I) refers to a pure surface (0).

In 1969, we concluded experimental research into heat transfer for boiling sodium in a pipe. Experimental results were obtained for a wide range of heat fluxes and vapor contents. On the basis of the experimental data, a method has been proposed for securing a stable boiling process by introducing at the entrance to the channel a small amount of an inert gas.

In 1969, at the Department of Heat Transfer we continued research into the flow and heat transfer of conducting liquids in the electromagnetic field. In particular, data were obtained on the stability of flow in a longitudinal magnetic field. /23

With the aid of experimental apparatus, making it possible to realize a laminar flow with Re numbers up to 10^4 without the magnetic field, data were obtained on the effect of a longitudinal magnetic field on the stability of laminar flow. It was established that a longitudinal magnetic field significantly increases the stability of laminar flow.

Investigation of Mass Transfer Processes

The Department of Mass Transfer has continued comprehensive studies of the hydrodynamic, mass transfer, and heat transfer characteristics of two-phase non-equilibrium flows at low and high pressures. In 1969, experimental relationships were obtained among the true volume vapor contents, wall temperatures, circulation multiplicity factors, and degrees of the lack of equilibrium along the length of the channel in two-phase stationary flows.

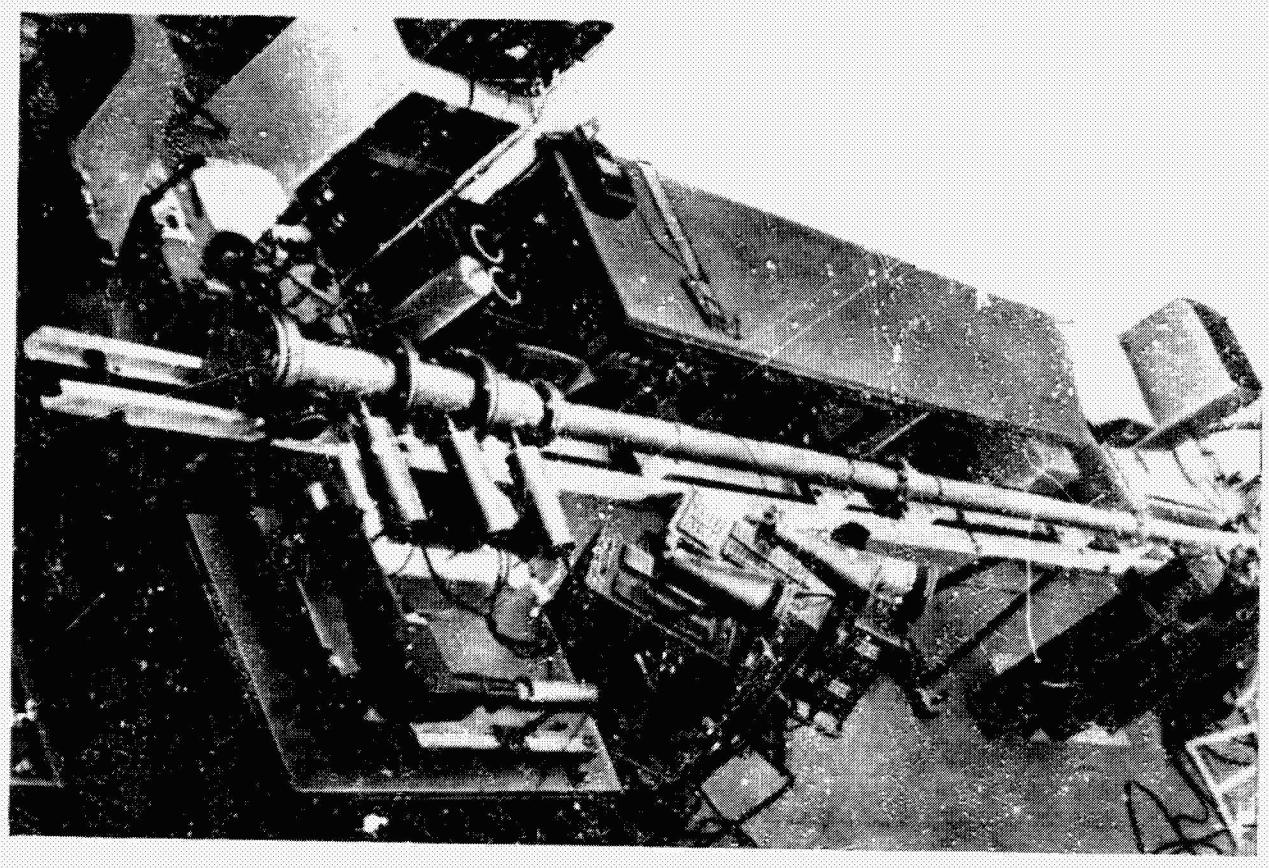

Figure 8

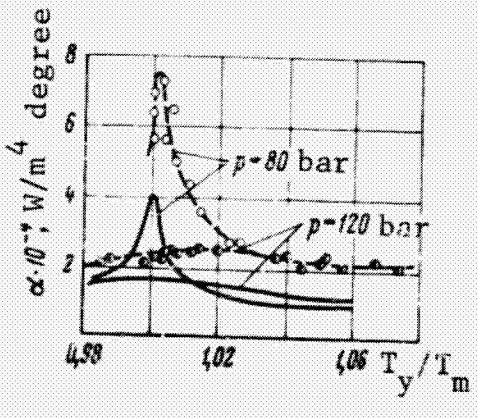

Figure 7.

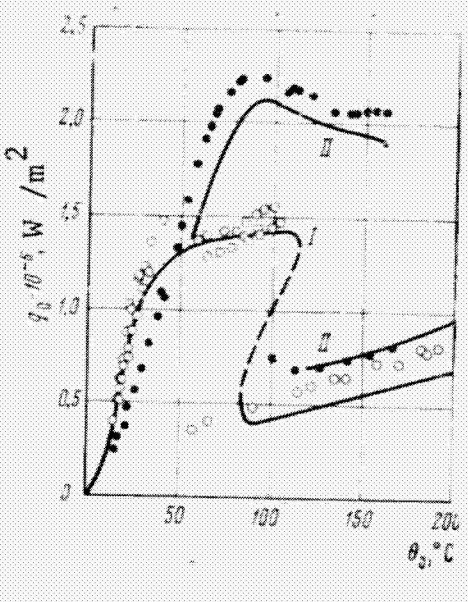

Figure 9.

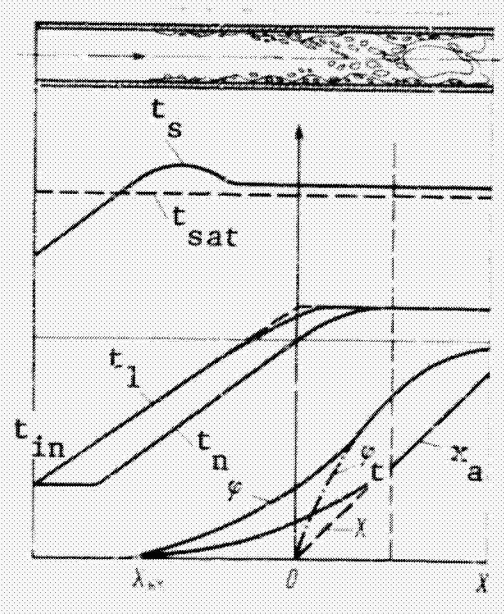

Figure 10.

Figure 10 shows the relationships between the principal characteristics of two-phase non-equilibrium[1] and equilibrium flows[2] and the relative enthalpy X along the length.

An analysis of the obtained relationships for the first time enabled us to show clearly the close connection between the mass and energy transfer processes, and the hydrodynamics of two-phase non-equilibrium flows.

From Figure 11 it is evident, for example, that the flow structure determines to a considerable extent the type of the boiling critical region and the heat load (q_{cr}) at which the critical region arises.

We see that in the pseudo-convective region [$(t_s - t_l/\Delta t_{ned}*) = 0.5 - 1.0$] heat transfer calculations may be done using the formulas for convective heat transfer. Intense boiling in the boundary layer begins for $(t_s - t_l/\Delta t_{ned}) > > 1.0$. At $(t_s - t_l/\Delta t_{ned} \approx 1.0$ the temperature of the wall first exceeds the value corresponding to a developed boiling process in an equilibrium two-phase mixture (Figure 12)[3]. At the same time one observed a break in the

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(1) t_s - temperature of the heated surface; t_n - temperature of the stream nucleus; t_l - the temperature of the liquid phase averaged over the cross section of the channel; ϕ - the true volume vapor content; X_a - the actual input-output vapor content expended.

(2) ϕ_t - is the true volume vapor content, and X is the weight input-output vapor content expended by weight.

(3) A graph of the dependence of t_s and K on X in the cross section at a distance of 190 mm from the entrance with a variable temperature of the liquid at the entrance for P = 1.2 bar, W_a = 1600 kg/m^2 sec, and q = 0.8 MW/m^2.

* Translator's note: This term not defined in original text.

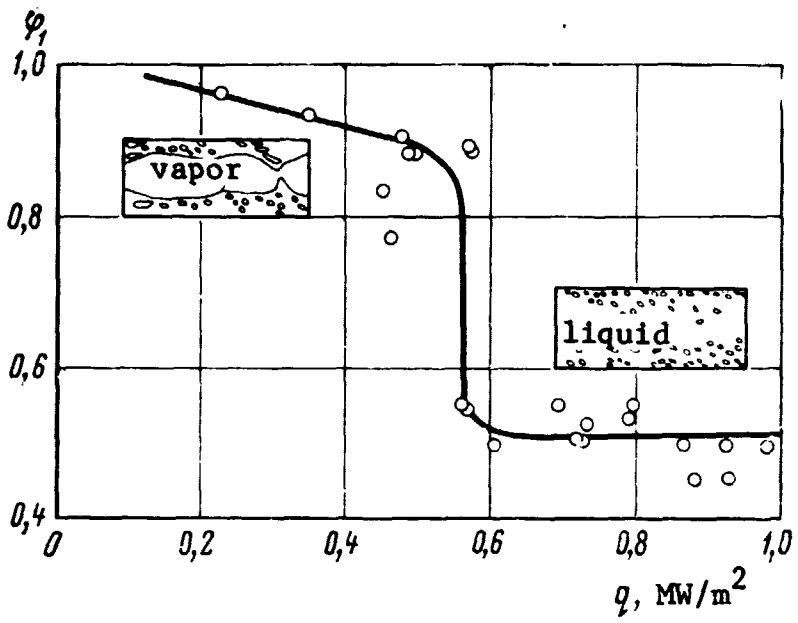

Figure 11.

curve showing the relationship between the circulation multiplicity factor (K) and the relative enthalpy (X). The method of translucence registers the appearance of vapor (ϕ) and the relative heat emission coefficient $\alpha_{boil}/\alpha_{conv}$ becomes greater than one. The Department of Mass Transfer worked out a method of controlling the intensity of vapor formation with respect to the local temperatures of /24 the heating element that allows us to control the intensity of vapor formation in various cross sections of the experimental pipe (nodes and antinodes) continuously during the entire experiment, and makes it possible to begin studies of the effect that ultrasonic oscillations have on the kinetics of the vapor formation process.

The second area in which the Department of Mass Transfer does research is the field connected with the use of ionizing additives in MHD installations.

In 1969, work continued on various aspects of the process involving the introduction of ionizing additives in open cycle MHD installations -- namely a highly concentrated aqueous solution of potassium carbonate.

A study was made of the temperature characteristics of steam generating pipes in which aqueous solutions of K_2CO_3 with concentrations from 20 to 73% by weight would be boiled. At a pressure of 50 abs. atm. heat emission coefficients for these solutions were determined, and the limits of deteriorating characteristics caused by a crystallization of salts on the heated surface were clarified.

Studies of the behavior of an additive in the gas channel of MHD installation with open cycle can be reduced to two basic tasks: a determination of the intensity of mass transfer in the stream of condensation aerosol and a study of the process of transition of K_2CO_3 into $KHCO_3$ in the stream of combustion products.

The experiments were conducted on both experimental stands and on model MHD installations U-02. The questions related to an introduction of ionizing additives were discussed in research studying the effectiveness of capturing submicron dust of K_2CO_3 (and $KHCO_3$) with the aid of a turbulent washer. The experiments have shown that this method makes it possible to capture over 99% of the additive and separate it out in the form of a solution. At the same time investigations were made of the transition of K_2CO_3 into $KHCO_3$ in the aqueous solution of potassium carbonate, with the latter being in contact with the combustion products of the natural gas. Data were obtained that would be of great practical significance in designing the MHD installations. /25

The Department also conducted research into the structure of water applying the techniques of wave spectroscopy.

The force field of an isolated water molecule was found together with the dependence of its electro-optic parameters on the force constant of the OH bond. The data obtained made it possible to calculate the intensities of the bands due to the valence oscillations of water in a number of complex groups. A comparison of calculations based on a model with experiment showed a good agreement ($\pm$ 10 - 14%).

A cell was built for high-temperature and high-pressure work, and experiments were made with $t \leq 275°C$ and $P \leq 65$ atm.

Silicon was used as a material for windows, and it indeed proved its worth.

Procedures were worked out using double-beam spectrometers to measure objects heated to 500°C and having geometric dimensions smaller than the dimensions of the image of the light source.

The Department of Mass Transfer also conducted research dealing with the processes of heat and mass transfer in the turbulent boundary layer of gas.

In 1969, we obtained the limiting relative laws of friction, heat transfer, and mass transfer for the turbulent boundary layer of low temperature plasma in the electric and magnetic field. A method of calculations has been developed for the turbulent boundary layer in the initial section of a channel with the blow-in of a cooling gas, and under true non-isothermic conditions. The method of calculation takes into account the mutual interaction between the boundary layer and the potential nucleus of the stream which may be considerable when intensive blow-in is used.

In cooperation with the Mechanics Research Institute of the Moscow State University, theoretical and experimental investigations were conducted in the field of hydrodynamics and heat transfer in the region where the boundary layer breaks off with the flow past a step and partition. Also a method of calculating the effectiveness of a gas barrier under these conditions was suggested.

Experiments were conducted dealing with the thermal interaction of the supersonic flow with a partition. The effectiveness of a gas partition was studied under these conditions.

Research in the Area of Physical Gas Dynamics

In the Physical Gas Dynamics Laboratory in 1969, an experimental /26
investigation of the composition of a gas stream behind a strong shock wave was made under conditions of incidence on an inclined surface and with a mutual interaction of the shock wave with the barrier.

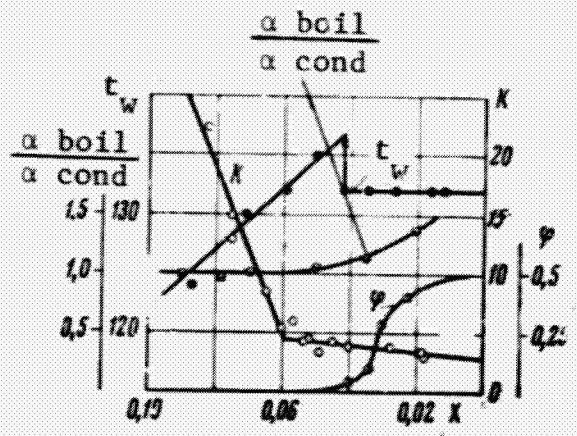

Figure 12

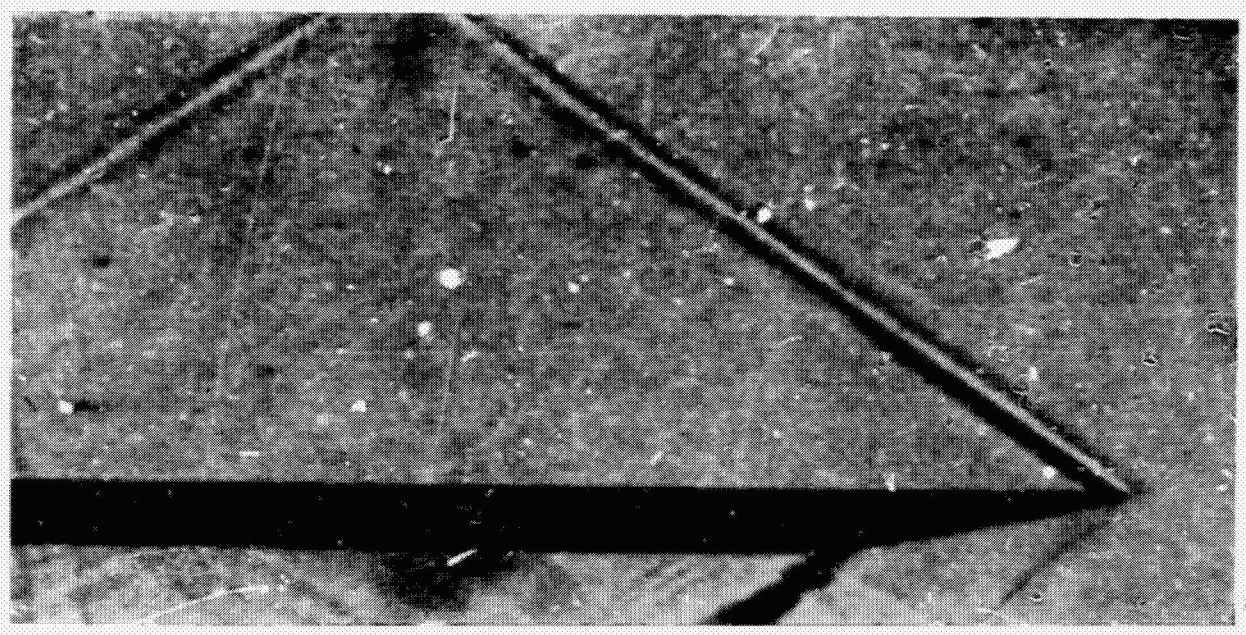

Figure 13

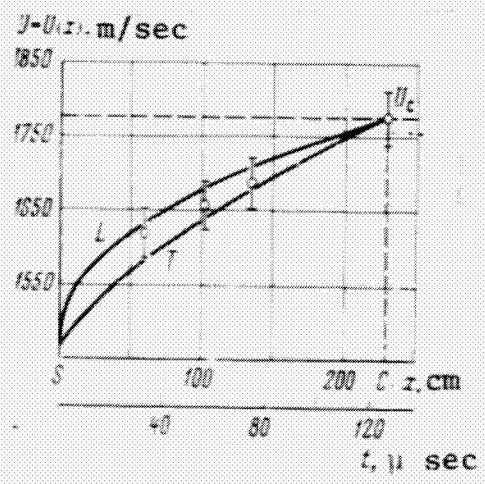

Figure 14

In the process of measuring the temperature of the surface of a wedge -- and pressure on the wedge surface, from which the shock wave is reflected -- it was discovered that in the regions with a double Mach reflection of the shock waves there appears a region of secondary increase of pressure and temperature of the surface, which is due to the braking of the flow relative to the surface of the wedge. In this region, the pressure and the heat flux into the wall are twice as large as those behind the Mach wave. By means of calculations based on the three-shock theory, limits were found for the parameters for which it is possible for the second triple point to occur and for the braking region due to a reflection of strong shock waves to take place.

The interaction of the flow behind the shock wave in the relaxing gas with a half-wedge is accompanied by the formation of Mach line whose direction depends on the extent of the physico-chemical transformations taking place in the flow behind the shock wave (Figure 13). Measurements of the directions of Mach lines and the flow velocity behind the shock waves in nitrogen have shown that, due to the growth of the boundary layer in a shock tube, the flow velocity U behind the shock wave increases from jump (S) to the contact surface (C), where it practically reaches a value equal to the velocity of the shock wave U_c (Figure 14)[4]. In the coordinate system connected with the jump, these conditions correspond to a complete stagnation of the flow. This circumstance must be taken into consideration when calculating gas parameters behind the shock wave, particularly in estimating the time the gas remains at a high temperature, which is usually defined as the ratio of the path traversed by gas from the front of the shock wave to the calculated value of the flow velocity. /27

Experiments aiming at determining the velocity and the M number of the stream in gaseous carbon dioxide and mixtures of carbon dioxide with nitrogen have shown that, as the concentration of CO_2 increases, the density of the stream becomes more and more inhomogeneous, and the scatter of the experimental values increases. Nevertheless, it may be shown that under these conditions

[4] L means laminar; T means a turbulent boundary layer.

flow Mach numbers are understated as compared with the calculations, and the flow velocity is too high.

In addition to an investigation of the gas dynamic stream parameters behind a shock wave, in 1969 measurements were also made to determine the profile of the electrophysical parameters behind a shock wave in a non-equilibrium gas (in cooperation with the Institute of Radio Engineering and Electronics of the Academy of Sciences of the USSR). In particular it was discovered that in argon behind a shock wave for $M \cong 10$, $P_0 = 2$ mm Hg the electron temperature lags behind the atom temperature. A calculation has been made to determine the profile of the electron temperature T_e for these parameters of the shock waves. In Figure 15, we have a distribution of the electron temperature T_e and the electron concentration n_e behind a shock wave in argon for $M = 11$, $P_0 = 2$ mm Hg. The region where an equilibrium electron temperature has been established is up to 5 cm in length. The Theoretical Division in 1969 continued to work out the theory of spacecraft heating when moving through dense atmospheric layers. In connection with this problem a theory of state of a non-equilibrium plasma formed behind the front of a strong shock wave is being developed. The objective of the theory is to determine the profile of the concentration of atoms, molecules, electrons, and ions behind the front of the shock wave, their distribution with respect to the energy states, and the temperatures of translational motion. Attention is mainly given to an investigation of ionization which determines the character of relaxation behind strong shock waves. Calculations of relaxation were made behind the front of shock waves in nitrogen at speeds 17 - 25 km/sec. In the velocity interval indicated, the double ionization of nitrogen becomes a process which determines to a large extent the state of the gas in the non-equilibrium zone. The value of the ionization time obtained depends non-monotonically on the wave velocity.

Work was completed that dealt with a study of the relaxation zone behind strong shock waves in air (v_c = 10 - 16 km/sec). As a result, an explanation was found for the appearance behind the front of an intense maximum of non-equilibrium radiation, and its quantitative description was given

(Figure 16)[5]. This made it possible to estimate the contribution of non- /28
equilibrium radiation to the heating of blunt bodies in a hypersonic flow.

The Theoretical Division in 1969 continued its research on complex gas dynamics, namely, the hypersonic flow past a body. For the axial region in the flow around a blunt body, the distribution of gas dynamic parameters was found, where account was taken of the viscosity, heat conductivity, and the energy transfer by way of radiation.

Extensive numerical calculations were made for various values of the velocities and density of the oncoming flow, as well as for various radii of curvature of the blunt body. An analysis of the results permitted us to establish a number of interesting relationships, characteristic of the heating of spacecraft at speeds exceeding the second cosmic speed. Thus, for example, it was established that at high speeds the total heat flux incident on a body very weakly depends on the radius (Figure 17), contrary to the notions held earlier. The correlation between the heat flux across a body and speed also turned out to be weaker as a result of a strong radiation cooling. A good deal of other relationships have been considerably modified. Those relationships were obtained earlier without radiation transfer being taken into consideration.

Research in the Area of Magnetohydrodynamics

The Plasma Division conducts theoretical and experimental research on nonstationary magnetohydrodynamic processes.

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(5) Intensity profiles of radiation I in the wavelength interval 0.55 - 1.0 μ: v_c - velocity of shock wave; P_1x - product of pressure before the front by the distance from the wave front. Solid curves - calculation; dashed curve - experiment.

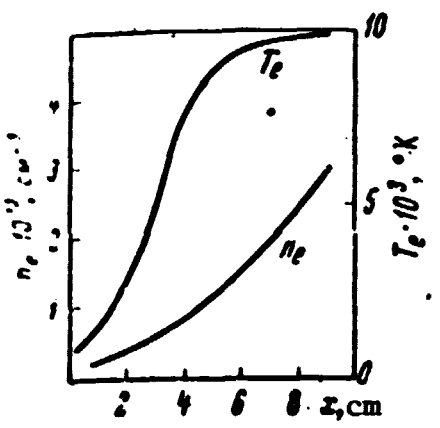

Figure 15

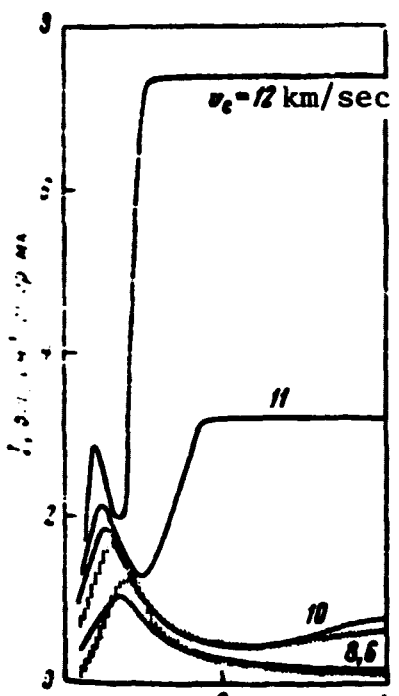

Figure 16

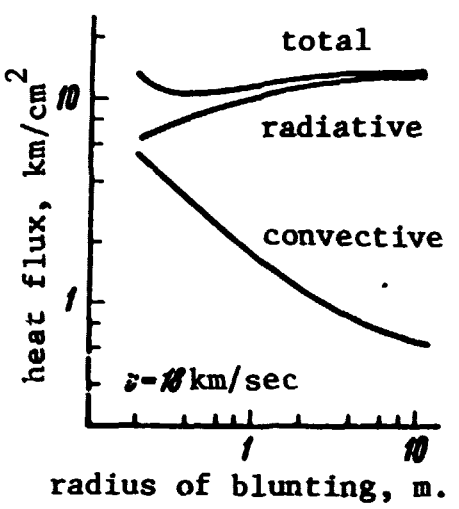

Figure 17

The principal concern of present research is to investigate the nonlinear effects accompanying the interaction of a fast-moving plasma with a magnetic field for large values of the magnetic Reynolds number and the magnetic pressure exceeding the gas pressure.

In 1969, we concluded work dealing with the technique of calculating the magnetohydrodynamic flow using the method of characteristics, and with the stability of shock waves in a magnetic field.

Complex experimental research dealing with the motion of a shock wave in a MHD channel under non-equilibrium conditions was concluded.

A theoretical investigation of the magnetohydrodynamic flow for large magnetic Reynold numbers was done in the Division of MHD installations.

It was shown that for sufficiently long channels with an iron magnetic system, the induced magnetic field is determined from a quasi one-dimensional Maxwell equation with the boundary conditions depending on the method used to close an external electric circuit. To calculate the characteristics of the MHD channel for large Re_m, a variational problem was formulated and solved involving flow of a compressible gas with variable electroconductivity. The channel characteristics turn out to be best when the external circuit was closed at the exit from the channel. In this case the magnetic field increased along the stream. With sufficiently strong electromagnetic interaction, the solution contains a segment of the boundary extremum on which the magnetic field is constant and equal to the saturation induction. /29

N70-37069

DEVELOPMENT AND STUDY OF NEW HEAT-RESISTANT STRUCTURAL MATERIALS

SECTION 3

In 1969 work was continued whose goal was to develop and study heat-resistant structural materials to be used under long-term operational conditions, and applied mainly in the construction of MHD generator units and parts. In 1969 *research was conducted with a veiw toward producing electrode materials for MHD generators of the open-cycle type* based on zirconium dioxide stabilized with ytrium oxide, lantanium chromite, and alloyed lantanium chromite. /30

New technology was developed to obtain lantanium chromite in quantities sufficient for technological use. For this purpose, La_2O_3 and CrO_3 were alloyed in an arc furnace by means of an alternating current. Samples of lantanium chromite were prepared, and its electric and physical properties studied. The usual four-probe technique was used in the investigation. The measurement was done in vacuum using an alternating current. The results of the measurements are shown in Figure 18: 1 - $LaCrO_3$; 2 - 75% $LaCrO_3$ + 25% ZrO_2/La_2O_3; 3 - 50% $LaCrO_3$ + 50% ZrO_2/La_2O_3; 4 - 25% $LaCrO_3$ + 75% ZrO_2/La_2O_3; 5 - ZrO_2, stabilized 16.6% (mole) La_2O_3.

Technology was also developed and a study was made of the electrophysical properties of lantanium chromite alloyed with the oxides of the alkali and rare earth metals. It was established that lantanium chromite, with admixtures of calcium oxide of 5 to 10% by weight — obtained by means of electric alloying followed by annealing thinly dispersed powders — possesses a level of conductivity necessary for obtaining energy from the channel of a MHD generator. Figure 19 shows isotherms of conductivity for lantanium chromite as a function of the content of the alloying admixture.

In 1969 developments were made in the technology of obtaining electrodes based on chromium carbide alloyed with tungsten and rhenium.

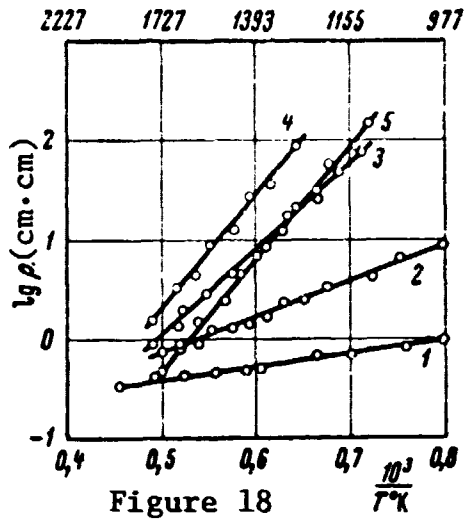

Figure 18

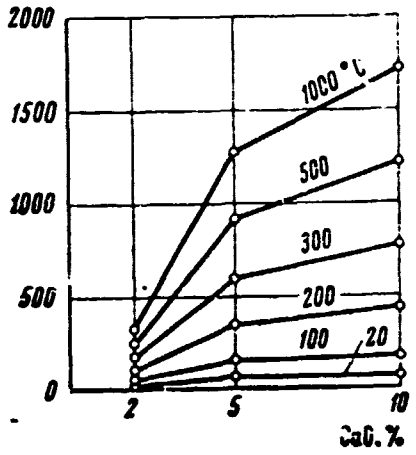

Figure 19

An introduction of rhenium increases the recrystallization temperature of the ceramic material, increases it strength, etc. The same phenomenon is also observed when tungsten is introduced. A technological procedure was develcped to produce large-scale goods of ceramics based on chromium carbide alloyed with high-melting metals such as titanium and molybdenum (electrodes can be produced 80 mm in diameter and 140 mm in height). /31

For the electrode materials for MHD generators with a closed cycle, the Division of Heat-Resistant Materials developed a method and technology of obtaining protective coatings made of tantalum carbide on carbon-graphite products.

The coating of a product can function in a 10^{-5} - 10^{-6} mm Hg vacuum at a temperature above 2500°C. Progress was made in the technology of the diffusive welding of niobium carbide with metallic niobium.

In 1969 *work was continued on an experimental investigation as to the possibilities of developing the technology and studying the properties of fire-resistant types of concretes,* based on magnesium or aluminum oxides and various high-melting bonding materials (cement rich in aluminum oxide, alumnophosphate bonding, magnesium bonding). These investigations were conducted in two principal directions:

-- development of electro-insulating materials needed to insulate the walls of the MHD generator channel;

-- exploration and development of heat insulating materials needed for the lining of various thermal units of an MHD generator.

Investigations were made to develop the technology and improve the properties of magnesium concrete, which happens to be one of the promising materials that might be used to insulate the channel of an MHD generator.

A study was made of the mechanism and kinetics of the hardening of magnesium cement, and as a result the conditions of the formation of the hydrated phases of variable composition (magnesium hydroxide and magnesium oxichlorides) were clarified. To decrease the penetration of the alkaline admixture, technology was worked out to obtain products of concrete that would possess lower porosity and the necessary thermal resistance. Experimental verification was made of various construction and technological variants of designing the insulating walls of a channel made of magnesium concrete. It was established that the optimum version is the module version based on the hardening of concrete modules to a metal with the aid of preliminary heating of the copper sublayer, followed by soldering with soft and hard solders. Tests made of such walls in the channel of a model U-02 MHD installation for 60 hours have shown that the electro-insulating characteristics of the channel did not change signficantly, and the magnesium concrete itself possesses high thermal and erosive resistance (Figure 20). An investigation was continued of concrete rich in aluminum oxide on an aluminophosphate binding. The work was in the stage of developing the technology, studying the properties, and making tests on model machines.

Studies were made to develop the technology and study the properties of /32
thermal insulating fire-resistant types of concrete. These studies made it possible to make a selection and give recommendations as to the lining of various units of the MHD generator that are under thermal stress, such as the convective shaft of the steam generator (magnesium concrete), hot blowout air-duct (magnesite), exit cone of the combustion chamber (concrete rich in aluminum oxide). Studies were made to determine the interaction between the heat insulating fire-resistant types of concrete with potash melts. It was established that the decisive factor, in the durability of refractory materials working in contact with an alkaline admixture, consists in making sure that the thermal unit operation is stationary. A disturbance in the operation (long halt) leads to hydrating potash condensed in the pores of the material, and this causes

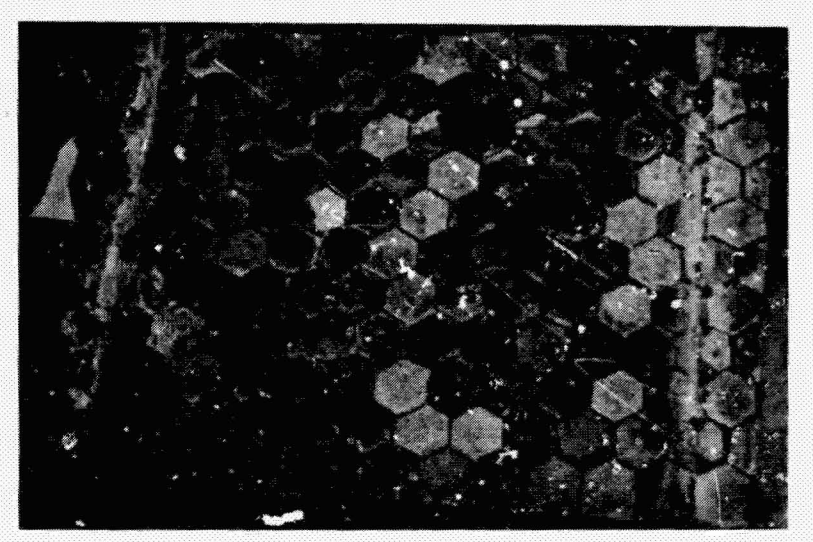

Figure 20

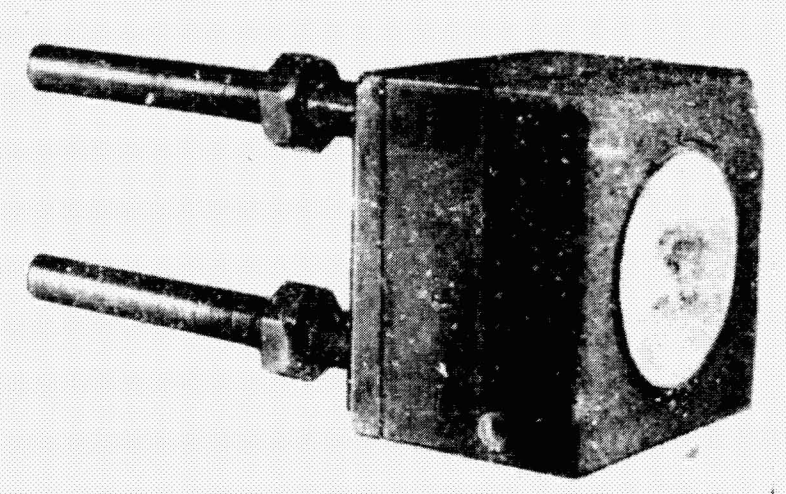

Figure 21

disintegration of the material.

In 1969, at the Division of Heat-kesistant Materials, an experiment was performed to obtain fused materials.

The arc technique of fusing has many advantages. It makes it possible to increase the purity of the refined crystal structure, and considerably enhances the thermal resistance, resistance to the action of corrosive elements, and other materials. For example, the melting point of the ordinary technical magnesia (low-melting admixtures of the oxide) is 2000 - 2100°C. Thermal resistance of the ordinary technical magnesia after annealing undergoes 3 to 4 changes; that of the fused magnesia, 28 changes. The design of the experimental setup took into account the possibility that it might be operated by both alternating and direct current, in vacuum, and in an inert gas. An electric arc in the crystallizator of the furnace develops and maintains temperatures above 3500°C. /33

In order to study the kinetics of the annealing of oxide ceramic at temperatures from 1750 to 2000°C, as well as for rapid analysis of the behavior of structural elements in contact with a stream of combustion products, the Division built a gas-flame stand. In 1969 tests were conducted on this stand at a hot surface temperature up to 2000°C. In Figure 21 we have shown an electrode

Figure 22

Figure 23

unit after tests on the gas-flame stand.

In 1969 at the Division of Heat-Resistant Materials, a procedure was developed and the kinetics of ceramic annealing was studied on a dilatrometric apparatus at temperatures up to 3000°C.

By means of this device, a study was made of the kinetics of annealing heat-resistant materials, and the melting point of compcsitions based on the boron-carbon system was determined.

In 1969 a number of studies was completed on structural defects and their effect on the properties of materials. In particular, the influence of the defects on the resistance of materials in a stream of low-temperature plasma on the experimental device and the U-02 device was established.

In the complex disintegration mechanism, we can distinguish three typical processes which, to a large extent, determine the rate of disintegration:

(1) evaporation and mutual interaction along the faces of crystals;

(2) disintegration of the surface at points with macro- and micrc-defects;

(3) removal of whole particles, separated from each other by seats of disintegration, from the surface of the electrodes by means of the stream.

The electron-microscopic pictures (x 2000), obtained by the technique of two-stage replicas of copies, show the surface of electrodes made of Zr_2O + + Y_2O_3, that were tested on the U-02 device. Figure 22 shows the surface of

an electrode with an ideal structure in which a slow disintegration proceeds according to the first mechanism. Figure 23 shows the surface of a rapidly disintegrating electrode, possessing a defective structure (second and third case).

The Division of High-Temperature Processes built and used models using /34 high-frequency and impulsive plasma heating to study the process of obtaining niobium from its compounds in a plasma. The possiblity was demonstrated of reducing niobium pentoxide to lower oxides, and partially to niobium in an impulse plasma in a suspended oxide layer.

A study was made of the process of reducing niobium pentoxide with carbon (graphite) in a boiling layer, heated by micro-arcs. According to the data obtained by means of X-Ray structural analysis and chemical analysis at temperatures above 1500°C, the main reaction product is niobium carbide (impurities up to 0.2%).

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DEVELOPMENT OF INSTALLATIONS FOR DIRECT CONVERSION OF HEAT INTO ELECTRICAL ENERGY BY MEANS OF MHD-GENERATORS AND OTHER NEW ENERGY DEVICES

SECTION 4

Stationary Power Installations Provided with MHD-Generators /35

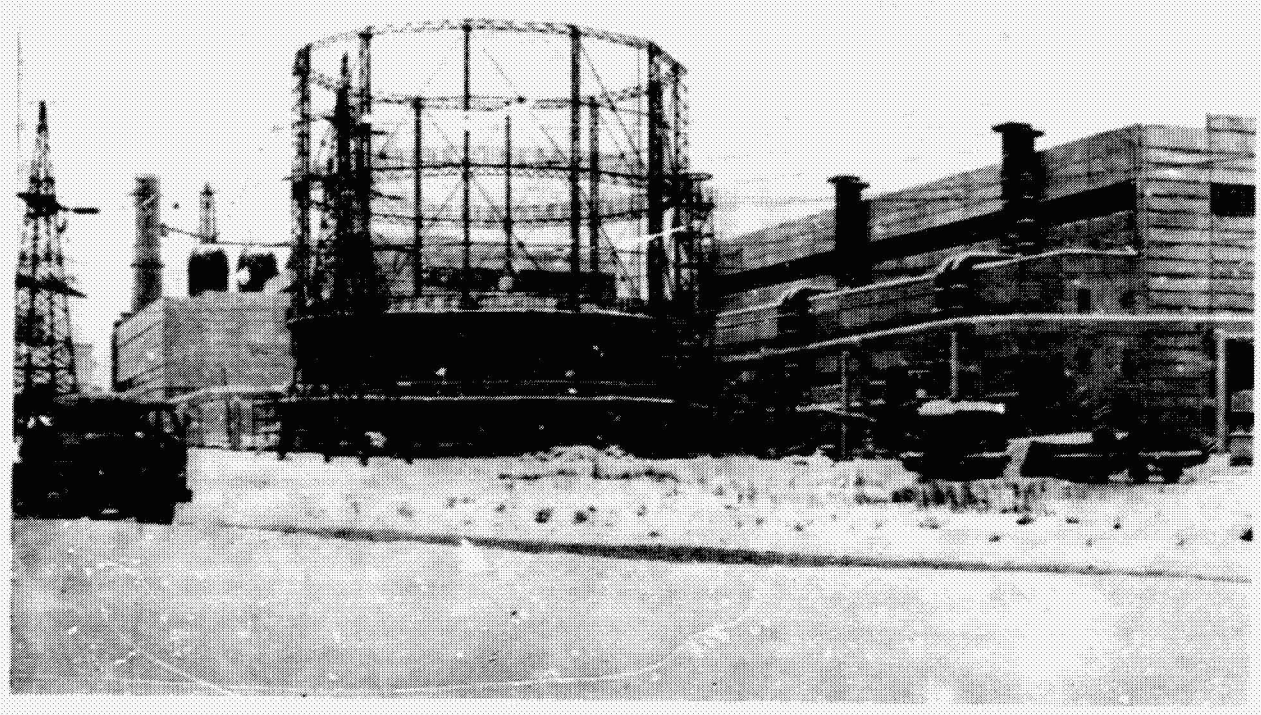
Last year the High Temperature Institute provided the scientific supervision of construction of an experimental industrial power station with a MHD-generator of 25,000 kW capacity, installation U-25 (Figure 24). The Institute carried out several research operations connected with starting-adjustment procedures. In the course of these investigations, the details of gas dynamics and heat processes were studied in the channel of installation U-25. Special attention was devoted to the variable starting modes during the operation of the basic equipment of the installation: the air preheater, combustion chamber, MHD-generator and steam generator. On the basis of these investigation results, a graph of the performance characteristics of installation U-25 was made.

The basic experimental work for testing non-standard equipment and adjustment of the MHD-generator channel was carried out at model installation U-02 and on stand "Temp". During these investigations, successful tests of the separate elements of the installation U-25 channel were reported, demonstrating satisfactory performance of the module-cooled electrode and insulated walls of the channel.

Research was carried out on metallic electrodes of steel and copper and also on ceramic electrodes of silicon carbide and zirconium dioxide.

During the metal electrode tests, primary attention was devoted to the study of the behavior of micro-arcs on the surface of the electrodes with

a



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b

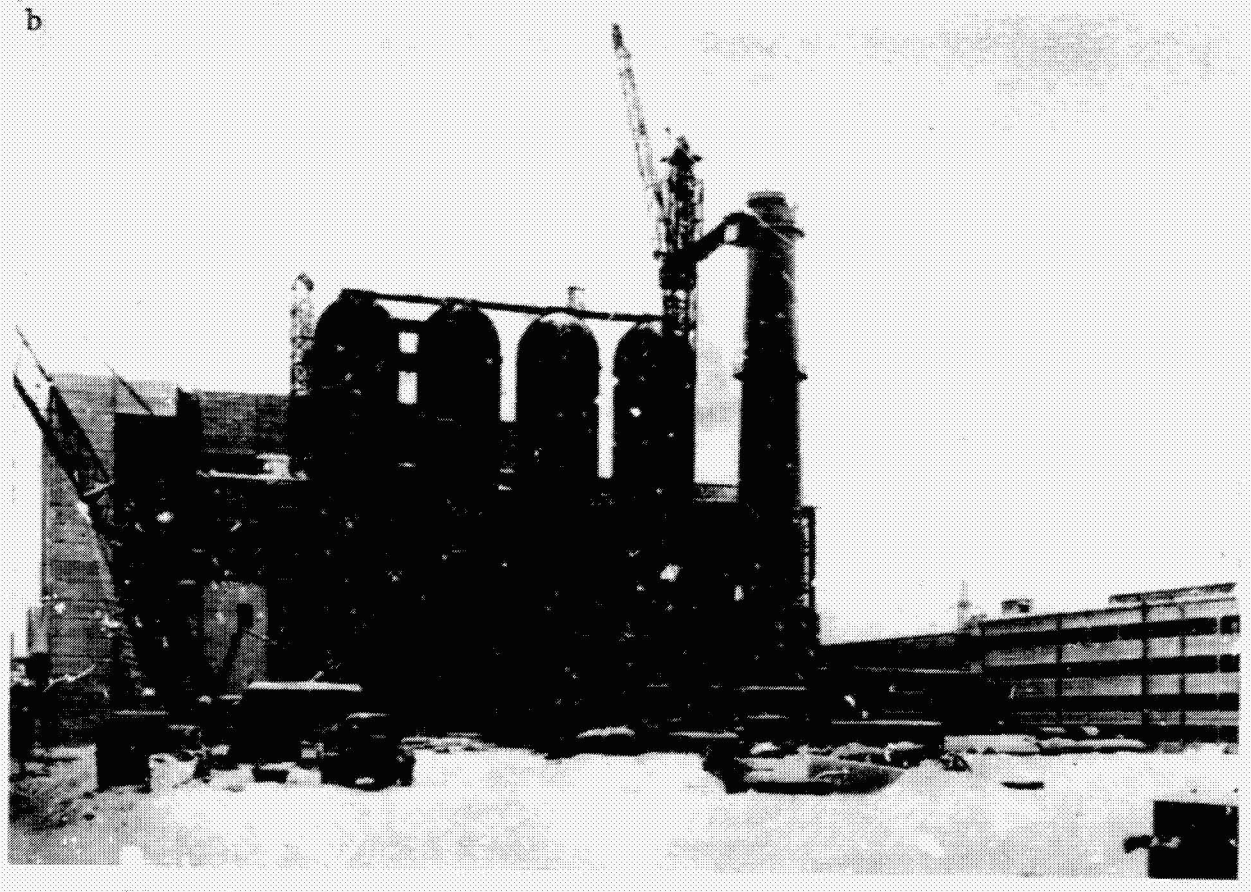

Figure 24

Figure 25

various currents and magnetic field induction. Also the effect of electrodes with different positions and shapes were studied.

In Figure 25, micro-arcs are depicted on the surface of the electrodes. Their study was carried out by means of high-speed photography using rapid SKS movie cameras and a high-speed SFR-L photodetector with special optical systems. With the concurrent photodetection of micro-arcs, various electrical and thermal parameters of the electrodes were recorded. /37

The research permitted a study of the behavior of arcs, their number and intensity, and established special points of the electrodes where powerful high-intensity arcs are observed which result in noticeable localized erosion of the electrodes. The studies showed that a film of potassium compounds from the flow collecting on the electrode surface has a considerable influence on the behavior of arcs.

These model electrode studies carried out over a wide range of currents in the MHD-generator channel of the large experimental industrial installation U-25 have considerable significance for the development of powerful MHD generator channels.

The studies completed in 1969 of the silicon carbide and zirconium dioxide electrodes established the range of surface temperatures at which diffusion and arcing regimes of current flow are observed. The result of an additive and temperature fields was also determined, as well as the effect of advancing the electrodes in the flow on their stability during prolonged tests.

The studies made showed that the emergence of the pinched discharge (arc) by no means always leads to intensified disintegration of an electrode. In the case when the flow of current in the cathode region is determined by

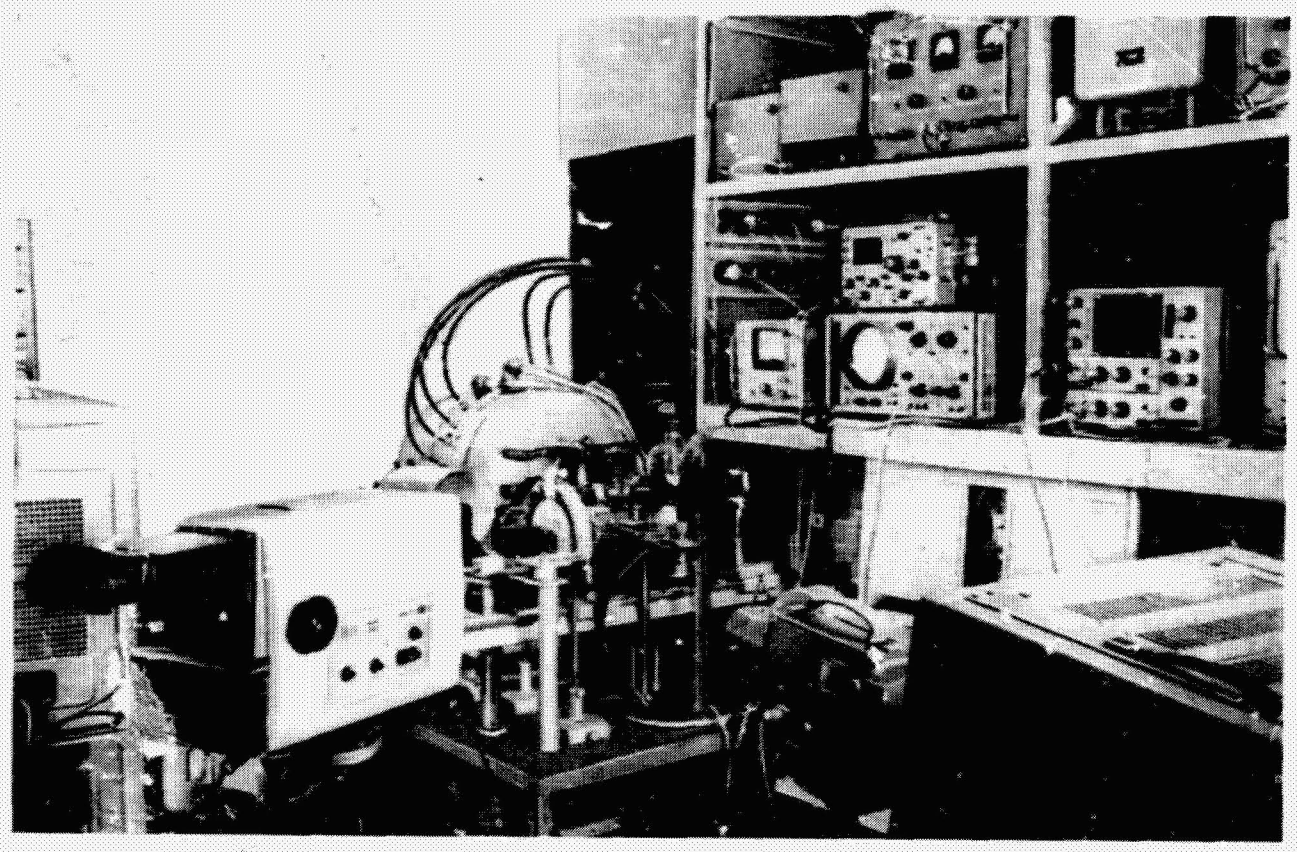

Figure 26

autoelectronic emission, the cathode spots present cause practically no disintegration of the electrode. However, transition to the thermal autoelectronic mechanism of emission gives rise to quasi-stationary cathode spots which intensify the electrode disintegration.

In 1969, experimental equipment for studying the dynamics of processes adjacent to the electrodes was built which permitted electro-optical detection of spots with time resolutions down to 10^{-8} sec with simultaneous measurement of charged particle concentration in the cathode region with time resolutions as low as $5 \cdot 10^{-8}$ sec. With this equipment it was successfully shown that the variation of the cathode spot current with the formation of discharge is connected for the main part with the variation of charged particle concentration (from 10^{14} to 10^{16} per cm^{-3}) in the cathode region, leading, as far as was ascertainable, to a change in the emission mechanism.

To develop a quantitative theory of the cathode region for high-current discharge which could explain the observed experimental phenomena, it is necessary

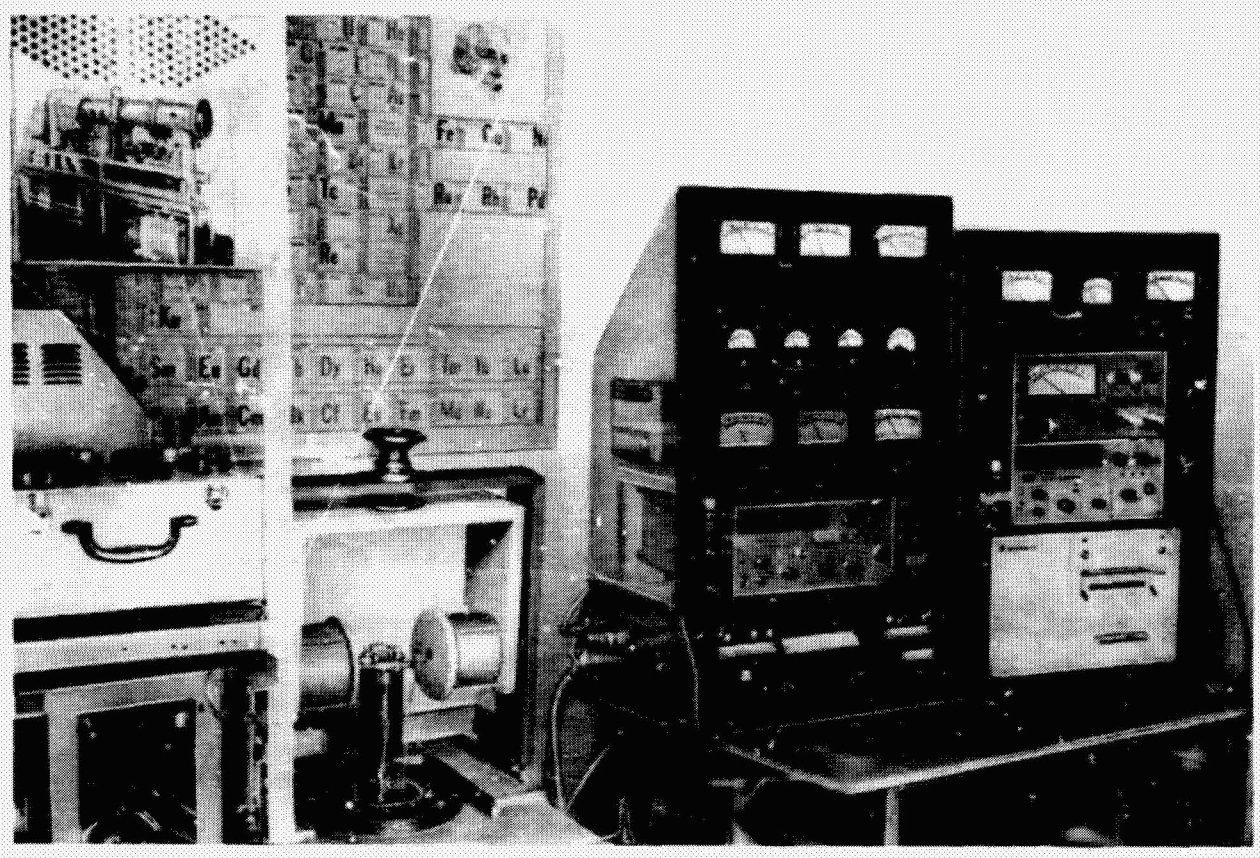

Figure 27

to take into account the elementary processes which determine the ionization in the cathode region. One of the basic constants which determine these processes is the ionization cross section by electron collision of the vaporized electrode meterial. At the present time, sufficiently reliable and accurate /38 data on the ionization cross sections of various elements are extremely limited. In connection with this, in 1969 equipment was built for measuring the ionization cross sections by electron collision of the vapors of materials with low vapor tension (Figure 27). Measurement of the ionization cross sections was performed by the method of crossed modulated beams. The results of the measurements for the metals of the barium group are cited in Figure 28. The results obtained revealed that, in view of the substantial difference of ionization cross sections and resonant charge exchange in the cathode region, intensive diffusion of ions to the cathode arises which induces a change in the ion concentration in the cathode region in time. Thus, the characteristic times of ion concentration growth in the cathode region are near those which were experimentally observed for the change in the emission mechanism. In this

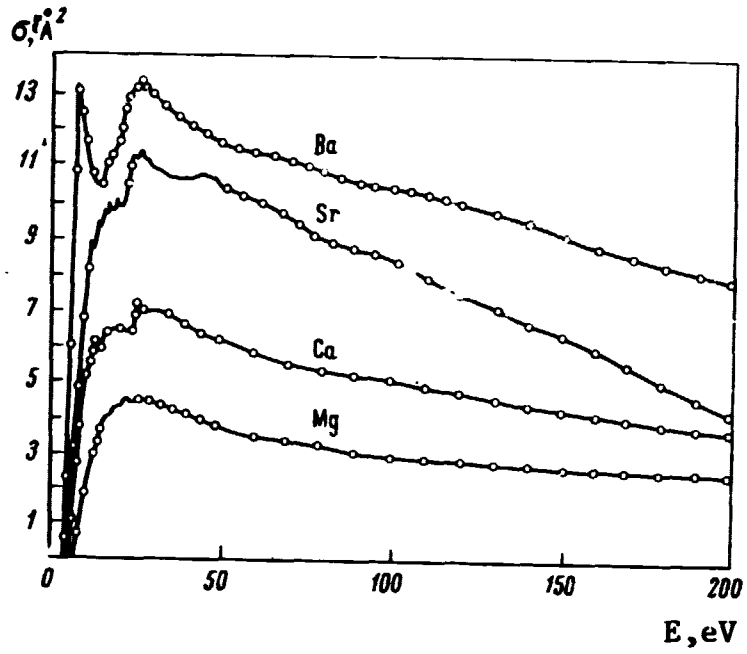

Figure 28

manner, the process of cathode spot formation in the pinched discharge was successfully described theoretically.

The study of the formation of high-current discharge on electrodes covered by a layer of a poorly ionizable additive with a high vapor tension disclosed a new form of high-current discharge: diffusive discharge. Support of this type of discharge is characterized by extremely weak disintegration of the electrode material. Investigation of the high-current discharge on electrodes covered directly with an additive in the MHD-generator channel has shown that the intensity of the electrode disintegration process by pinched discharge is reduced by a factor of ten. /39

Studies of the insulated walls were made according to the following basic guidelines: /40

(a) theoretical computational studies of the effect of electrophysical insulation properties on MHD-generator characteristics, and preliminary choice and investigation of the electrical insulation properties of materials in the presence of an atmosphere of combustion products and compounds of potassium in the high-temperature installations;

(b) study of electrical characteristics of insulated segments of the cooled module walls.

The work is carried out both in model studies and at specially completed installations which are mounted during the experimentation in various sections of the channel. This work includes studies on: the significance of contact

resistance between the conducting surfaces and the plasma; the shunting action of a single metal of the wall; diffusion of a gas flow of additive compounds onto the wall, including chemical analysis of deposits and reactions of the additive with various elements of the construction materials of the wall; development and testing of the construction and fabrication technology of insulated channel walls of the MHD-generator.

Among the insulation materials tested in 1969 were magnesia compounds, samples of fused magnesium oxide, strontium zirconate and hafnate, fused and granular magnesium oxide with various grain sizes and aluminum oxide. We note that no chemical reaction of the sample material with the additive was detected when samples of strontium zirconate and hafnate from the surface in contact with the flow were subjected to analysis.

For improving the thermal resistance of the samples, this quality of a material can substantially influence its future prospects as an insulator in a MHD-generator channel.

Along with the electrode and insulated wall tests, temperature and conductivity measurements are also performed in the MHD-generator channel.

The influence was studied of a non-uniform temperature distribution in the plasma on the optical temperature which is determined by the method of spectral line reversal. The results obtained enable one to find the maximum plasma temperature by the measured optical temperature if the relative distribution of temperature in the radiation source is known.

A method was proposed and experimentally checked for finding the temperature distribution near solid surfaces through the use of voltampere characteristics of the gaseous interval between surfaces. The temperature distribution can be obtained if one changes the contents of the weakly ionizing additive in /41
in the gas under investigation.

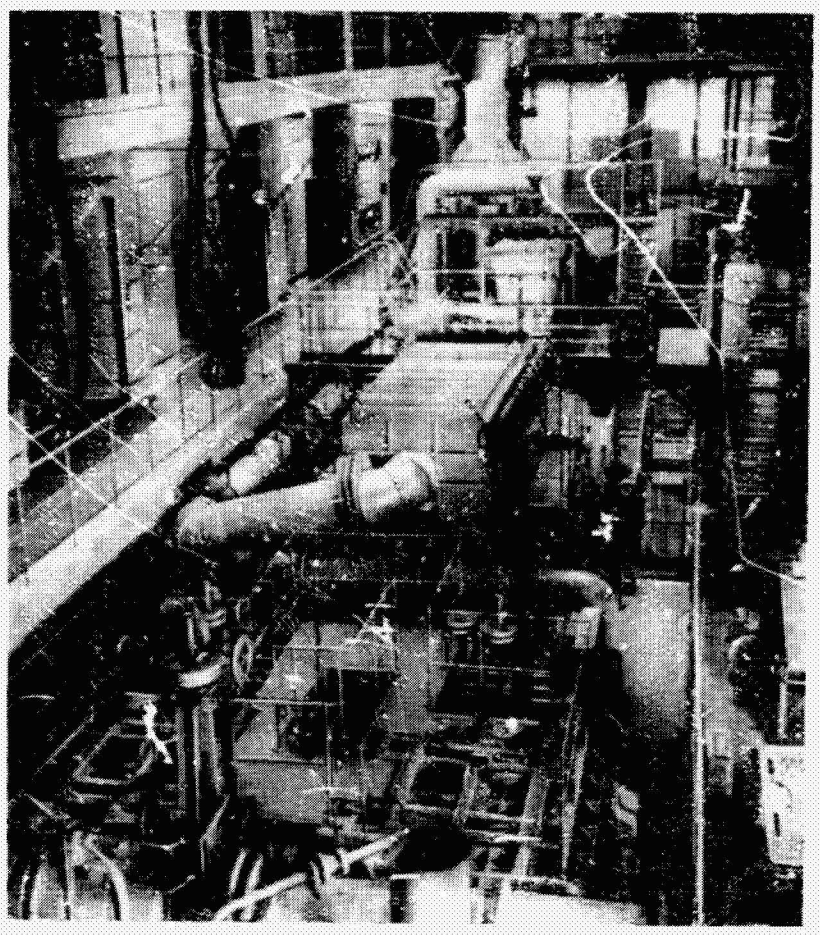

Figure 29

The experiments carried out have permitted us to determine the most promising avenues of research for producing a long-lived wall construction and optimally choosing the form and size of construction elements, as well as material to complete them.

In 1969 experimental studies were continued on the high-temperature regenerative air preheater (Figure 29) with a spherical adapter for both independent operation (with a bypass) and joint prolonged operation in the circuit of installation U-02.

The total operational time of the air preheater in heating air to 1500°C near the end of 1969 was already 3,000 hours. The last two start-ups of the air preheater lasted over 800 hours each. Under separate operating conditions, the air heating reached 1700°C and higher. In these experiments, the consumption of air being heated was changed from 0.4 to 1.2 kg/sec.

Experimental profiles have been obtained of the temperature distribution along the height of the spherical adapter and refractory lining in the heat exchange units of the regenerator. These were made for various temperatures /42
of air heating and aqueous equivalent correlations of the heated air and combustion products of the heating medium.

Analysis of the experimental data with respect to the hydraulic resistance of the spherical adapter in the high-temperature heat exhange units of the air

preheater has confirmed the known relationships for the special adapter with respect to hydraulic resistance, which were established earlier with comparatively low-temperature gases.

Oscillations of the thermal parameters (pressure, temperature and composition) of the heated air were studied for the regenerator cycle. The heating and cooling times of the heat exchanger were also specified.

In the year 1969, preliminary design and research efforts were completed on the multi-stage semiconductor inverter equipment connected to the MHD-generator of the U-25 installation.

In this operation, the first experimental results of the multi-element inverter equipment connected to the MHD-generator of installation U-02 were used. All basic design and construction decisions were first checked out experimentally, leading to their use in the engineering design and subsequent completion of the semiconductor multi-element inverter of the U-25 MHD installation.

In 1969, the multi-stage inverter installation I-30 was designed, assembled, installed, and put into operation on thirty pairs of electrodes for the open cycle MHD-generator U-02-0.

The installation "Tiristornyy Klyuch" was designed and manufactured and has passed preliminary tests. It is designed for non-contact rapid discharge of a high-current d.c. circuit, which has a concentrated inductance in the form of a superconducting solenoid.

In the same year, the performance of an MHD-generator using an equilibrium argon potassium plasma in a wide range of Hall numbers was studied on installation "Start". We discovered that the experimentally measured performance characteristics of the MHD generator turn out to be two orders of magnitude lower than those computed. The basic cause responsible for lowering the performance characteristics is the inhomogeneity of the flow arising on account

of the relatively cold boundary layers at the electrode walls.

Thus, when the ratio of electrode wall temperature to the core temperature of the flow equals 0.5, the Hall number increase from 2 to 25 leads to a lowering of the relative currents of the short circuit and Hall fields from $1.5 \cdot 10^{-1}$ to $5 \cdot 10^{-3}$. The increase of the relative wall temperature from 0.35 to 0.70 when the Hall number equals 15 leads to an increase of the rela- /43
short circuit current to $4 \cdot 10^{-2}$. It has been shown that electrodes projecting across the boundary layer have significantly better performance characteristics in comparison with electrodes situated flush with the wall.

On installation "Start", the electrical insulation properties of the MHD-channel walls and insulation of elements in the circuit under operating conditions were studied.

It was shown that the influence at high temperatures of an alkali metal additive substantially worsens these properties. A means of measuring the duct wall insulation properties under working conditions was worked out. It was demonstrated that, when the temperature of the insulated wall is raised from 1200° to 1900°K, wall insulation improves by two orders of magnitude.

In the year 1969, preliminary experimental data on the operation of an MHD-generator with a non-equilibrium plasma were obtained. Tests were completed on the operation of a pre-ionizer of the simplest type of construction. The generator performance, it was revealed, improves by over an order of magnitude when a pre-ionizer is used.

Thermal efficiency studies were made of the combined open cycle MHD power plants with various methods of achieving the high temperatures of the combustion products. The following methods of obtaining high temperatures were considered as possibilities for steady-state power production:

-- regenerative heating of air;
-- enrichment of air with oxygen;

-- preliminary thermochemical pre-processing of the fuel (pyrolisis, vapor, and mixed conversion).

Data were obtained on the effects of the enumerated techniques for achieving high temperatures on the thermophysical and electrical conductivity properties of the plasma, as well as on the parameters and geometry of the MHD-generator and other steam turbine equipment of the power plants. From the standpoint of the thermal efficiency of the MHD steam power plants, the method of enriching the air with oxygen has an advantage with respect to the relatively low oxidizer heating temperature (up to 800 - 1,000°C). For a higher oxidizer heating temperature, MHD power plants using thermochemically pre-processed fuel have better results. For example, heating air to 1,500°C and the thermochemical reaction products to 1,200°C yields efficiencies of 55 - 60% and higher for power plants with moderate MHD-generator length (10 - 13 meters).

A theoretical study was made of the MHD generator channel and effects, and their influence on the thermal efficiency of the power plants.

The problem of plasma flow in the end zones of a linear sectional MHD-generator was formulated and solved. Expressions describing the end effects /44
were obtained, making it possible to calculate the influence on generator performance of end effects. End effects depend strongly on the nature of the magnetic field drop behind the generator electrodes, as well as on the geometry, plasma conductivity and velocity, the magnetic field induction, and load factor of the generator.

Research on Development of Liquid Metal MHD Power Plants

Theoretical and experimental studies of problems connected with the development of liquid metal MHD power plants were continued in 1969.

Theoretical studies in this area were directed towards working out optimum thermal designs and cycles with the determination of parameters and operating media; the studies were also directed toward choosing the logical sphere

of application of MHD plants with a liquid metal operating medium.

In 1969, it was shown that the use of an MHD installation plant for stationary power production as a superstructure to the usual steam turbine cycle yields effective power plant efficiencies on the whole on the order of 50%, with a comparatively moderate maximum cycle temperature (900 - 1200°C).

Several experimental studies on accelerating devices were completed for liquid metal MHD installations with model operating media of water and mercury.

Various systems were studied for starting the steam-water injector in the open cycle and the steam-mercury injector in the closed system. Studies on the steam-water model yielded interesting data on the operational limitations of the injector. The start-up systems which were developed ensure optimum geometery of the flow portion of the injection.

Research on Development of Superconducting Magnetic Systems of MHD Generators

In the course of several years, the Institute Laboratory of Superconducting Magnetic Systems will carry out developmental studies on MHD-generator superconducting (magnetic) systems.

The basic directions in this work are:

-- research and development of new superconducting materials (jointly with metallurgy and cable institutes);

-- study of the physical processes which occur in superconducting magnetic systems for normal phases, and magnetization processes of superconducting windings;

-- optimization of superconducting magnetic systems of MHD-generators.

Besides these studies directly connected with the problem of developing large-scale superconducting magnets, systematic study is carried out in the laboratory on the behavior of superconducting materials in variable magnetic fields and the operation of magnetic systems under non-stationary conditions. /45

Along with the research program, the laboratory provides scientific guidance of the planning of large-scale superconducting magnetic systems and devotes a great deal of attention to the practical use of superconducting devices. In Figure 30, a magnetic system of the saddle type is shown in the process of winding, designed for a model MHD-generator. In 1969, the Institute was awarded the first prize Honorary Certificate for Achievements of the USSR National Economy (CANE) for the first experimental application of a superconducting system in pulsed MHD generators. Members of the Institute were awarded with medals of the CANE.

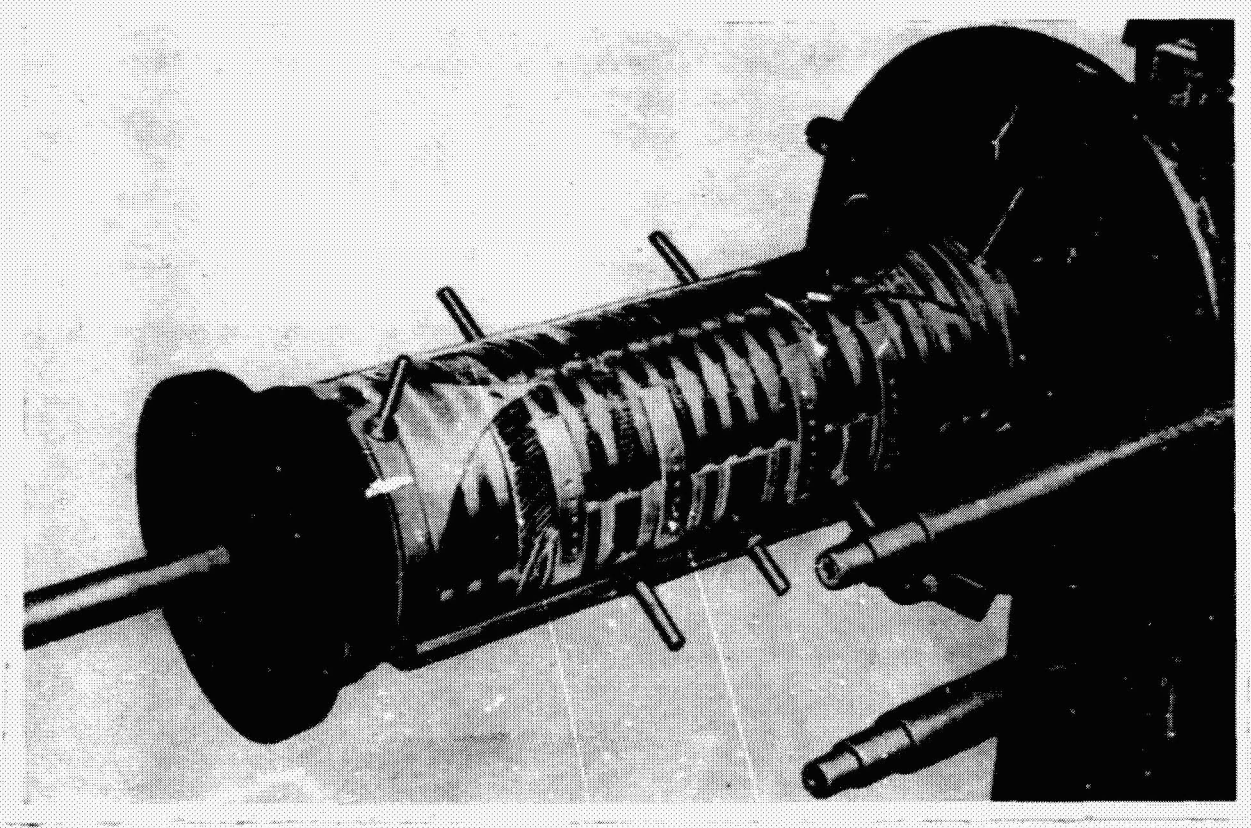

Figure 30

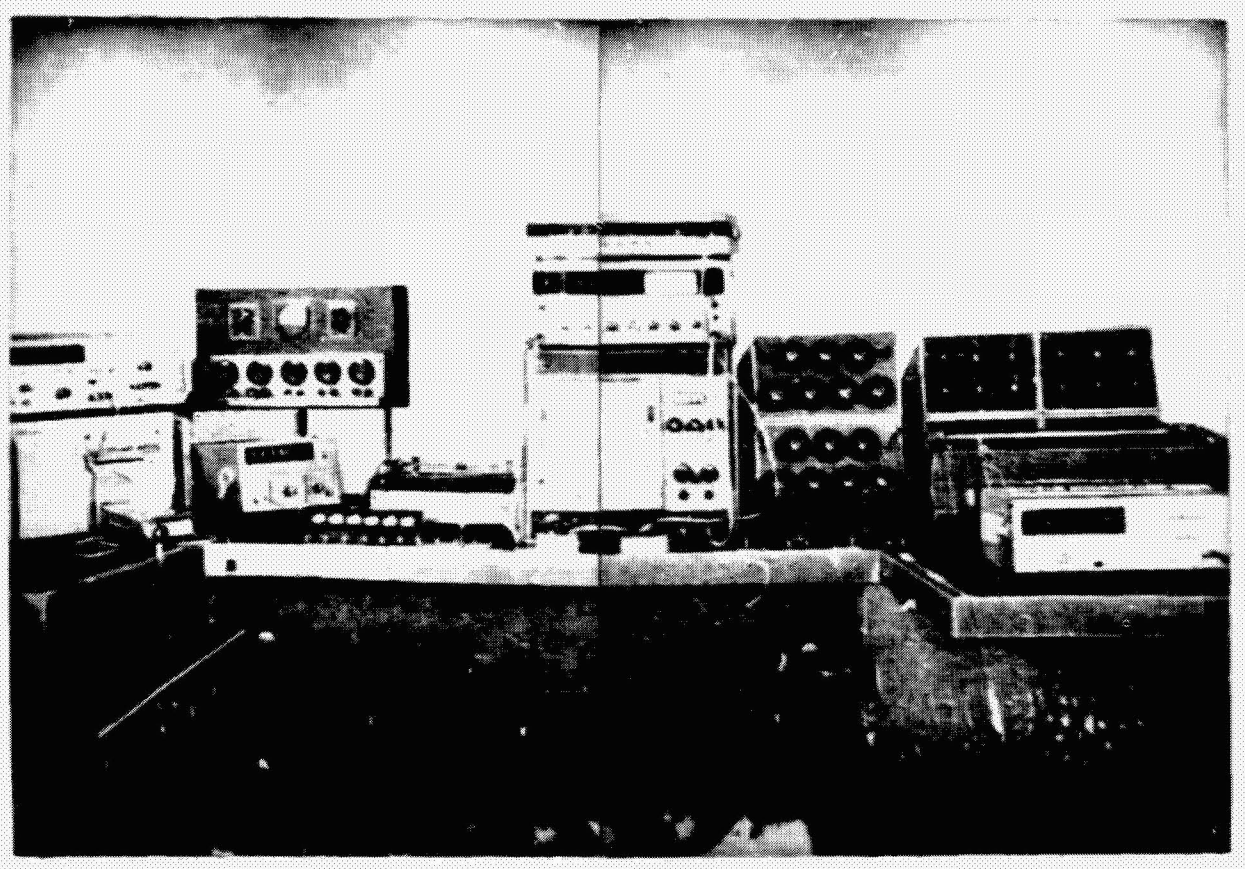

Figure 31

A new stage of studies was carried out in 1969 on the conditions of thermal equilibrium of a combined superconducting cable, in which the current is divided between a superconductor and a normal metal.

This stage of research was characterized by the fact that measurements were performed on modern materials which were obtained through metallurgical technology by the method of joint deformation of the superconducting and normal metal. Special attention was devoted to developing experimental methods to study the regions of unstable thermal equilibrium of a combined superconductor. The experimental equipment on which these studies were carried out is shown in Figure 31.

Studies were continued on the influence of a changing magnetic field on the current flowing along a superconductor of type II. /46

It is known that hysteresis losses arise in a sample of non-ideal type II superconductor located in a changing magnetic field. In the absence of an

external current flowing through the sample, these energy losses are compensated by the device which produces a variable magnetic field. If one sends a direct current from some external source through the sample, then the magnitude of the hysteresis losses must change somewhat, since in this case the distribution of induction in the sample material changes. The essential question is whether there is some effective resistance for the direct current in this case (whether part of the hysteresis loss is compensated by the source current) or equivalently, whether the displacement current will damp out in a closed superconducting circuit with a variable magnetic field in the material of which the circuit is made. Findings of the experiments carried out earlier in 1968 indicated that the effective resistance to a direct current arises only in the case when the external magnetic field amplitude exceeds a certain threshold value larger than the first critical point of the field. The essentially new result obtained in 1969 was the discovery of the influence of the strength of the constant component of the magnetic field and an external current flowing /47 through the superconductor on the threshold values of the variable field amplitude. The threshold value of the variable field decreases monotonically with the growth of the current and average field strength.

The linear dependence of the effective resistance on the frequency (in the range 0.01 - 0.1 Hz) confirms the hysteresis nature of the phenomenon under study. It was ascertained that the effective resistance depends linearly on the current and the alternating current amplitude and is a function of the average field. In 1969, development of a theory which explains the indicated phenomena with good quantitative agreement with experiments was concluded.

Studies on Intra-Cycle Preparation of Power Fuel

In 1969 the Institute continued its studies on the development and introduction of a comprehensive way to use high sulfur petroleums in power production.

Engineering plans for equipment and a complex design task were completed for a gasification system for petroleum of a large heat and electric power

plant (HEPP), which uses nearly two million tons of high-sulfur petroleum per year. Incorporation of the method of intra-cycle preparation of fuel at such a plant allows emissions of sulfurous anhydride into the atmosphere to be reduced by 90 - 95%. Savings per station of 10 - 15 million rubles per year may thus be obtained, in comparison with the use of low sulfur boiler fuels at petroleum processing plants.

New designs for generation of thermal and electrical energy have been worked out, permitting the use of the proposed method of intra-cycle fuel preparation with maximum economy. In particular, design of a steam central heating plant was worked out.

The primary advantages of the specified design over a steam turbine HEPP of the same power are:

(1) for nominal operation according to the heat load, fuel savings are achieved of 5 - 8%;

(2) capital expenditures are substantially reduced for construction of such a HEPP (of the order of 20%) because of:

-- elimination of hydroelectrical equipment for recirculating water passing into the condenser because of the absence of the latter;

-- replacement of the cumbersome steam boiler, in which the heating medium is kept at atmoshperic pressure, by a compact steam generator where fuel burning takes place under high pressures;

(3) capacity to change the heat load of the plant independently when a given electrical load is retained;

(4) the technological system for using high-sulfur petroleum is greatly

simplified and savings are made because of the elimination of the supercharging turbocompressor unit, because the steam plant has compressed air, and because of the reduction of heat-transfer surfaces. /48

Studies on the Problem of the Power Fuel Balance in the Power Fuel Economics of the Country

The primary scientific task of the Department of Complex Problems of Power Engineering lies in the study of the country's major complex problems of power engineering, the most advanced methods for producing electrical and thermal power and forms of power resources which are likely and promising for these methods of production. In 1969 the Department carried out studies to determine:

(a) the most probable changes in the relative economy of conventional and new types of power plants in the long range power fuel balance of the country, and

(b) the most likely conditions for the promising use of new types of power plants in electrical power systems.

The studies were carried out jointly with other academic institutes and institutes in other fields. This work is based on the use of the mathematical modeling method and the theory of large systems in power engineering.

APPENDIX

Articles, inventions, and books of the staff of the High-Temperature Institute of the USSR Academy of Sciences, published in 1969, as well as reports of the Institute staff at the international conferences held in 1969. /49

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